The Weather and Climate of Australia at the
Last Glacial Maximum

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Abstract

The global climate has experienced four glacial cycles in the last 420,000 years, with each cycle characterised by a prolonged period of cooling culminating in maximal glaciation followed by a brief warm period. The most recent period of maximal glaciation is termed the Last Glacial Maximum (LGM) and occurred about 21,000 years ago. We currently live in one of the warm periods. The global climate is changing, and it is becoming more important to understand the extremes of the climate system and how well our modelling capability can capture those extremes.

There has been a modelling intercomparison project established to examine how global general circulation models compare in simulating past climates, including the LGM. Analysis and comparison of these model results has been presented for many parts of the globe, but there has not been a comparison of the different model results over the Australian region. This thesis aims to fill that gap and explore the simulated LGM weather and climate of Australia and its drivers in more detail. Comparison with proxy evidence is also undertaken, and inconsistencies seen in the literature addressed.

The Australian climate at the LGM was believed to be generally cooler, drier and possibly windier from proxy evidence in the literature. In the comparison done here the mean temperature and precipitation fields from most models show cooler and drier conditions, with some seasonal variability, but there are some strong outliers. It was found that the differences were not dependent on model resolution, but that the surface parameterisation were highly important for these fields.

The shifts in the circulation were examined both in the model results and with a study of the non-linear link between the wind, surface moisture and dunes, which are a proxy for past winds. All the models simulate a southward shift in the westerlies in the Australian region. This is strongly driven by the prescribed sea-surface temperatures. Australia’s current wind regime is
conducive to dune building. However, the binding effect of soil moisture (or vegetation) is strong enough to limit present day movement, whereas in the drier climate at the LGM there was a capacity for sand movement. The analysis of dune orientations did not produce conclusive evidence for how the westerlies might have shifted at the LGM.

An apparent enigma in the proxy evidence at the LGM is the high lake levels in Australia’s south east, while most inland lakes were dry. Previous authors believed that the precipitation was still low, but the high lake levels were driven by lowered potential evaporation. The hydrological cycle was generally depressed in the LGM simulations, but the potential for evaporation remained high. Thus an alternative hypothesis is posed based on increased runoff due to a known shift in the vegetation types and a lag in the timing of the runoff due to snowmelt.

The analysis here shows that our capacity to simulate climates quite different from the present is still developing, but that model results can help explain apparent inconsistencies in the reconstruction of past climates from proxies.
Declaration

This is to certify that

(i) the thesis comprises only my original work towards the PhD,
(ii) due acknowledgement has been made in the text to all other material used,
(iii) the thesis is less than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.
Acknowledgements

My most sincere thanks to my supervisor, Ian Simmonds. His breadth of knowledge from the guts of the atmospheric model to the people involved in the wide range of topics that this thesis touches upon was always priceless. His irresistible good cheer and persistence on pushing certain topics made the experience at times frustrating, but I think produced a better thesis in the end. I also extend great thanks to Jim Bowler, who, although he did not want to be named as a supervisor, gave me excellent guidance on all things paleo, and how to keep the big picture in perspective. Jim also agreed to have me along on the ‘mega Mungo’ field trip which provided me with huge insight into the practical side of dating sediments.

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and reminding me that we all need time out every now and again. Lyn Bettio for encouraging us all to get from in front of our computers and play soccer, and loving the pretty things in life. And of course Bev, though not strictly a student in Earth Sciences, for highlighting how good the interaction really was in the met group, and helping me enjoy many an iced-chocolate.

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## Contents

1 Introduction .......................... 1
   1.1 Background .......................... 1
   1.2 Survey of global modelling studies of the LGM ................. 2
   1.3 Palaeoclimate Modelling Intercomparison Project (PMIP) ........... 4
   1.4 Aims of this thesis .................. 6
   1.5 Outline ............................. 6

2 Proxy evidence of the Australian climate at the LGM .......... 9
   2.1 Reconstruction of Australia’s LGM temperature and precipitation from proxies .................. 10
   2.2 Proxy evidence of temperature and water availability .......... 14
       2.2.1 North Australia .................. 14
       2.2.2 Central Australia ................. 16
       2.2.3 South western Australia .......... 19
       2.2.4 South eastern mainland Australia .. 19
       2.2.5 Tasmania ........................ 21
   2.3 Paleo-circulation from proxies .......................... 21
       2.3.1 Age ............................. 24
   2.4 Synopsis ................................ 30
       2.4.1 Temperature and moisture availability ................. 30
       2.4.2 Paleo-circulation .................. 31

3 Model description, boundary conditions and mean climatology 33
   3.1 Introduction .......................... 33
   3.2 Melbourne University General Circulation Model ................ 33
   3.3 10 m wind calculation .................. 36
       3.3.1 Magnitude of winds at 10 metres .................. 37
3.3.2 Turning from the lowest sigma level to 10 metres ........................................ 38
3.4 Boundary conditions for the Present Day simulation ...................................... 40
3.5 Present Day simulation results and comparison with data ............................... 42
3.5.1 Data ............................................................................................................ 42
3.5.2 MUGCM Present Day mean results ......................................................... 43
3.6 LGM boundary conditions ............................................................................. 50
3.7 Climate regions .............................................................................................. 58
3.8 Chapter conclusion ......................................................................................... 63

4 Simulated LGM and Present Day climate: I. Temperature and precipitation 65
4.1 Introduction .................................................................................................. 65
4.2 Temperature ................................................................................................. 68
4.3 Precipitation ................................................................................................. 75
4.3.1 Simulated MUGCM LGM precipitation .................................................. 75
4.3.2 PMIP simulations of LGM precipitation ............................................... 75
4.4 Discussion .................................................................................................... 84
4.5 Chapter summary and conclusions .................................................................. 86

5 Simulated LGM and PD climate: II Winter circulation 87
5.1 Introduction .................................................................................................. 87
5.2 Circulation descriptors .................................................................................. 88
5.2.1 Definitions of 'westerlies' ....................................................................... 88
5.2.2 Sea-level pressure .................................................................................. 90
5.2.3 Mean zonal wind .................................................................................... 93
5.2.4 Zonally averaged temperature and stream function ............................... 96
5.2.5 Measures of baroclinicity ....................................................................... 97
5.2.6 Automatic cyclone identification and tracking ....................................... 101
5.3 Shift in zonal wind simulated by PMIP models .......................................... 103
5.4 Chapter summary and conclusions .................................................................. 106

6 Hydrological changes and the moisture budget 119
6.1 Introduction .................................................................................................. 119
6.2 Water balance and lake levels ...................................................................... 120
6.3 Total atmospheric moisture ......................................................................... 125
6.4 Variability of precipitation .......................................................................... 130
6.5 Air parcel trajectories to precipitation events ............................................. 136
# Table of abbreviations and frequently used symbols

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMIP</td>
<td>Atmospheric Modelling Intercomparison Project</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>Used after a date to indicate an uncalibrated radiocarbon age</td>
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<tr>
<td>CLIMAP</td>
<td>Climate: Long-range Interpretation, Mapping and Prediction</td>
</tr>
<tr>
<td>DJF</td>
<td>December, January, February (austral summer)</td>
</tr>
<tr>
<td>EPILOG</td>
<td>Environmental Processes of the Ice age: Land, Oceans, Glaciers</td>
</tr>
<tr>
<td>GCM</td>
<td>General Circulation Model</td>
</tr>
<tr>
<td>JJA</td>
<td>June, July, August (austral winter)</td>
</tr>
<tr>
<td>LGM</td>
<td>Last Glacial Maximum</td>
</tr>
<tr>
<td>MAM</td>
<td>March, April, May (austral autumn)</td>
</tr>
<tr>
<td>MUGCM</td>
<td>Melbourne University General Circulation Model</td>
</tr>
<tr>
<td>NCEP2</td>
<td>NCEP/DOE reanalysis II</td>
</tr>
<tr>
<td>PD</td>
<td>Present Day</td>
</tr>
<tr>
<td>PMIP</td>
<td>Paleoclimate Modelling Intercomparison Project</td>
</tr>
<tr>
<td>ppmv</td>
<td>parts per million by volume</td>
</tr>
<tr>
<td>$q$</td>
<td>Sand shifting potential</td>
</tr>
<tr>
<td>RDP</td>
<td>Resultant sand Drift Direction</td>
</tr>
<tr>
<td>SON</td>
<td>September, October, November (austral spring)</td>
</tr>
<tr>
<td>SST</td>
<td>Sea Surface Temperature</td>
</tr>
<tr>
<td>TDP</td>
<td>Total sand Drift Potential</td>
</tr>
</tbody>
</table>
List of Figures

2.1 Location of LGM paleo proxy evidence of local water availability and temperature. Each number refers to reference locations in Table 2.1. Changes in available moisture are to the left of the number, (D=dryer at the LGM, W=wetter), temperature changes to the right, (C=cooler). Number 11 refers to three locations. Topography shading: -120, 200, 400, 800 m. The region shown by grey shading is the approximate land extent at the LGM. Topography data is from ETOPO5 database. 

2.2 Dune orientation on the Australian landscape - from Jennings (1968).

2.3 Paleo dunes, (a) and lunettes, (b) and their direction and present day sand drifts, (c) and their direction (from Sprigg (1982)).

2.4 Frome relict dune forms, and the present day dune extensions, from Sprigg (1982).

2.5 Mallee relict dune forms, and the overlying present day sand-drifts, from Sprigg (1982).

2.6 Numbers referring to sites with age estimates, with details in Table 2.2 and in the text. Dune orientations across Australia, re-drawn from Wasson (1986).

3.1 Annual 1982-87 Reynolds sea surface temperatures minus 1979-88 annual GISST2.3. The increment is 0.2 degrees, negative anomalies are dashed.

3.2 DJF mean sea-level pressure. (a) MUGCM, (b) NCEP2, contour interval 5 hPa and (c) MUGCM - NCEP2, contour interval 4 hPa.

3.3 JJA mean sea-level pressure. (a) MUGCM, (b) NCEP2, (c) MUGCM - NCEP2, Contour interval 5hPa.
3.4 DJF Wind vector at 850 hPa height. (a) MUGCM, (b) NCEP2, (c) MUGCM - NCEP2, interpolated to R21 resolution, the reference vector length is drawn below each map in \( \text{ms}^{-1} \).

3.5 JJA Wind vector at 850 hPa height. (a) MUGCM, (b) NCEP2, (c) MUGCM - NCEP2, interpolated to R21 resolution, the reference vector length is drawn below each map in \( \text{ms}^{-1} \).

3.6 DJF temperature at 2m height. (a) MUGCM, (b) NCEP2, Contour interval 5 K (c) MUGCM - NCEP2. Contour interval 4 K, the lowest contour level is +/- 2 K. Negative contours are dashed.

3.7 JJA temperature at 2m height. (a) MUGCM, (b) NCEP2, Contour interval 5 K (c) MUGCM - NCEP2. Contour interval 4 K, the lowest contour level is +/- 2 K. Negative contours are dashed.

3.8 DJF precipitation. (a) MUGCM, (b) Xie and Arkin (1996, 1997). Contours at 0, 0.5, 1, 2, 5, 8, 10, 13, 16, 20, and 40 mm day\(^{-1}\).

3.9 JJA precipitation. (a) MUGCM, (b) Xie and Arkin (1996, 1997). Contours at 0, 0.5, 1, 2, 5, 8, 10, 13, 16, 20, and 40 mm day\(^{-1}\).

3.10 Mean MUGCM precipitation minus high quality gridded Australian precipitation, 1960-90. Both are interpolated to 1°x1° grid. (a) DJF, (b) JJA, contours are variable: -250, -200, -150, -100, -50, -25, -10, 0, 10, 25, 50, 100, 150, 200 mm month\(^{-1}\). Negative contours are dashed and the zero contour is bold.

3.11 Topography used in the MUGCM simulations for (a) PD, (b) LGM and (c) LGM-PD. The contour interval is variable, for (a) and (b) it is at 200, 1000, 2000 and 4000 m, while for the difference it is at 120, 1000 and 2000 m.

3.12 February SST, (a) PD and (b) LGM, contour interval 4°C; and (c) difference, contour interval 1°C. Negative contours are dashed, zero line bold.

3.13 August SST (a) PD and (b) LGM, contour interval 4°C; and (c) difference, contour interval 1°C. Negative contours are dashed, zero line bold.

3.14 Sea-ice extent prescribed in the MUGCM, for (a) February and (b) August. The PD extent is shown in darker grey, while the LGM is both dark and light grey.

3.15 Regions for which averages in tables are calculated. Central Australia is extended in such a way to include most of the arid regions.
4.1 The land extent at the LGM (shaded). The PD continental outlines are also drawn. .............................................. 66

4.2 MUGCM annual LGM temperature anomaly at 2 m. Contours at -25, -15, -10, -5, -3, -2, -1, 0, 1, 2, 3, 5, 10°C, negative contours are dashed and the zero contour is bold. Differences significant at the 99% level are stippled. .............................................. 69

4.3 LGM - PD Annual surface air temperature. PMIP simulations. Contours at -25, -15, -10, -5, -3, -2, -1, 0, 1, 2, 3, 5, 10°C, negative contours are dashed and the zero contour is bold. .............................................. 70

4.3 Continued... ........................................................................................................................................... 72

4.4 MUGCM annual LGM Precipitation. (a) Mean. (b) Anomaly from the PD. Contours at -13, -10, -8, -5, -2, -1, -0.5, 0, 0.5, 1, 2, 3, 5, 10 mm/day. Negative contours are dashed, zero contour bold. Regions of difference significant at the 99% level are stippled. .............................................. 77

4.5 As Figure 4.4, but for JJA ......................................................................................................................... 78

4.6 As Figure 4.4, but for DJF ....................................................................................................................... 79

4.7 LGM - PD annual precipitation, PMIP simulations. Contours at -20, -16, -13, -10, -8, -5, -2, -1, -0.5, 0, 0.5, 1, 2, 3, 5, 8, 10, 13, 16, 20 mm/day. Negative contours are dashed and the zero contour is bold. .............................................. 80

4.7 Continued... ........................................................................................................................................... 82

5.1 Annual mean low level winds from MUGCM for (a) PD, (b) LGM and (c) the anomaly. The reference vector is shown (ms⁻¹). ........................................... 89

5.2 JJA mean low level winds from MUGCM for (a) PD, (b) LGM and (c) the anomaly. The reference vector is shown (ms⁻¹). ........................................... 90

5.3 JJA MUGCM Sea-level pressure for (a) PD, (b) LGM and (c) LGM minus PD. Contour interval is 4 hPa for mean fields and 2 hPa for the anomaly, negative contours are dashed. Stippling on the anomaly indicates differences significant at the 99% level. ........................................... 92

5.4 JJA zonal wind, meridionally averaged between 5°S and 5°N. (a) PD and (b) LGM MUGCM simulation (Contour interval 5 ms⁻¹), and (c) difference (Contour interval 2 ms⁻¹). ........................................... 94

5.5 Southern Hemisphere 850 hPa zonal winds for each season in the (a) PD, (b) LGM MUGCM simulation, and their (c) difference. Contour interval: 2 ms⁻¹ ........................................... 95
5.6 JJA zonally averaged temperature from the (a) PD and (b) LGM MUGCM simulation (Contour interval 5 K), and difference (c) (Contour interval 1 K) .................................................. 98

5.7 JJA zonally averaged meridional mass stream function for (a) PD, (b) LGM from the MUGCM simulation. Contour interval: 20 x 10^9 kgs^-1. The difference (c) has a contour interval of 10 x 10^9 kgs^-1 .................................................. 99

5.8 JJA Eady growth rate at 500 hPa, the contour interval is day^-1. (a) is PD, (b) LGM and (c) the difference, with differences significant at the 99% level stippled .................................................. 100

5.9 JJA Cyclone System Density, MUGCM (a) PD and (b) LGM. The contour interval is 0.5, 1, 2, 4, 6, 10 x 10^-3 cyclones(^°lat)^-2. The contour interval for the anomaly (c) is 1 x 10^-3 cyclones(^°lat)^-2, and differences significant at the 99% level are stippled .................................................. 104

5.10 Winter cyclone depth, (a) PD, (b) LGM and (c) the anomaly. Contour interval is 1 hPa, negative anomalies are dashed. The contours are missing in regions with no cyclones. Differences significant at the 99% level are stippled .................................................. 105

5.11 MUGCM Southern Hemisphere 10 m zonal winds for winter in the (a) PD and (b) LGM simulations, and (c) the anomaly. Contour interval: 2 ms^-1. Differences significant at the 99% level are stippled .................................................. 107

5.12 Winter rainfall averaged over the south west of Australia (solid curve) overlaid on the latitude of the transition between easterlies and westerlies in NCEP2 10 m winds (dashed curve). Correlation is 0.75 .................................................. 108

5.13 Southern Hemisphere 10 m zonal winds for winter in the PD and LGM PMIP simulations, and their difference. Each sub-figure is clearly labelled with the model, and whether it is PD, LGM or LGM-PD. Contour interval: 2 ms^-1 .................................................. 109

5.13 Continued... .................................................. 117
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>A schematic of a theory for the moisture balance for two types of lakes, after Bowler (2003). The mountain represents the Great Dividing Range, and the left of the plot is near the centre of Australia. The curves represent annual precipitation and lake evaporation totals. Lakes with limited inflow, due to a small catchment or their position high up in the catchment, respond to the balance of precipitation and lake evaporation, while those with larger catchments, or further downstream, depend on inflow from rivers.</td>
</tr>
<tr>
<td>6.2</td>
<td>Annual LGM minus PD (a) precipitation (mm/day), (b) actual evaporation (mm/day), (c) surface soil moisture (proportion of saturated) and (d) potential evaporation (mm/day). Differences significant at the 99% level are stippled on the precipitation and evaporation plots.</td>
</tr>
<tr>
<td>6.3</td>
<td>MUGCM annual total column moisture (precipitable water) (mm). for the PD, (a), and (b) for the LGM. Contour interval is 5 mm.</td>
</tr>
<tr>
<td>6.4</td>
<td>LGM - PD Annual precipitable water, for all the models. Contours at 2.5 mm, negative contours are dashed and the zero contour is bold. Differences significant at the 99% level are stippled on the MUGCM plot.</td>
</tr>
<tr>
<td>6.5</td>
<td>Location of test on rainfall variability.</td>
</tr>
<tr>
<td>6.6</td>
<td>Frequency of rainfall amounts (mm/day) at points on Figure 6.5. (a) NT, (b) SA, (c) Central, (d) QLD, (e) VIC and (f) SWWA. Events are six hourly over two years. The frequency of zero rainfall is not included. Present day amounts are in light grey, to the left of the value, LGM in darker grey to the right.</td>
</tr>
<tr>
<td>6.7</td>
<td>Summer MUGCM trajectories to high rainfall events in the monsoon region. (a) PD and (b) LGM.</td>
</tr>
<tr>
<td>6.8</td>
<td>Winter MUGCM trajectories to high rainfall events in the south west of Western Australia. (a) PD and (b) LGM.</td>
</tr>
<tr>
<td>6.9</td>
<td>Winter MUGCM trajectories to high rainfall events in southern Victoria. (a) PD and (b) LGM.</td>
</tr>
</tbody>
</table>
6.10 Conceptual model of the atmospheric moisture fluxes over a land region, from Brubaker et al. (1993). $E$ is evaporation, $P$ is the total precipitation, $F^+$ is the inward flux of moisture and $F^-$ the outward, $P_m$ is the precipitation derived from local sources, while $P_a$ is precipitation from remote. $W$ is atmospheric moisture storage.

6.11 Relationship between the area over which the moisture recycling ratio is calculated with a tracer in the MUGCM and the value of the average recycling ratio, for the PD simulation. The recycling ratio calculated from averages is also included.

6.12 MUGCM PD recycling ratio for Australia using a tracer. (a) DJF, (b) MAM, (c) JJA and (d) SON.

6.13 MUGCM LGM recycling ratio for Australia using a tracer. (a) DJF, (b) MAM, (c) JJA and (d) SON.

6.14 The moisture recycling ratio’s dependence on area, calculated with Brubaker et al. (1993)’s equation for different values of evaporation and $F^+$. A, B, and C have the evaporation set to 1.0 mm day$^{-1}$, while $F^+$ is 5, 25 and 45 kg×10$^{12}$day$^{-1}$ respectively. D, E, and F have the same values of $F^+$, with evaporation set to 2 mm day$^{-1}$, and G, H, and I have evaporation set to 3 mm day$^{-1}$.

7.1 MUGCM anomaly of annual near surface air temperature. PD boundary conditions with LGM SST minus the PD. Contour interval: 1°C.

7.2 MUGCM anomaly of annual near surface air temperature. PD conditions with LGM solar input minus the PD. Contour interval: 0.1°C.

7.3 MUGCM anomaly of annual near surface air temperature. PD boundary conditions with LGM atmospheric carbon dioxide concentration minus the PD. Contour interval: 0.1°C.

7.4 MUGCM anomaly of annual near surface air temperature. PD boundary conditions with LGM topography, ice sheets and sea-level minus the PD. Contour interval: 1°C.

7.5 MUGCM anomaly of annual near surface air temperature. PD boundary conditions with LGM sea-ice extent minus the PD. Contour interval: 1°C.
7.6 MUGCM precipitable water anomaly from the sea-level and Northern Hemisphere ice-sheet experiment. (a) JJA, and (b) DJF. Contour interval is 2 mm. 170

7.7 Winter zonal wind at 850 hPa, zonally averaged from 100 to 160° longitude. Units: ms$^{-1}$. Simulations include PD, LGM, and PD with LGM sea-ice extent and PD with LGM SSTs. 171

7.8 Annual 850 hPa zonal wind, zonally averaged from 125 to 145° longitude in ms$^{-1}$. Simulations include PD, LGM, and PD with LGM sea-ice or SSTs or LGM sea-level (and Northern Hemisphere ice-sheets) or LGM CO$_2$ concentration or LGM solar input 171

7.9 JJA MUGCM zonally averaged (110-160°E) temperature anomaly. (a) Full LGM simulation minus PD (b) SST only simulation minus PD Contour interval is 1°K, negative contours are dashed and the zero line is bold. 175

7.10 MUGCM anomaly of the annual temperature at the lowest sigma level. LGM simulation with the updated Australian region SSTs minus the PD simulation. Contour interval : 1°C, negative contours are dashed and the zero line is bold. 176

7.11 MUGCM LGM annual low level cloud minus the PD. The mean cloud is expressed as a fraction, from 0 to 1.0. Contour interval: 0.05. 177

7.12 MUGCM LGM, with SSTs updated in the Australian region, annual low level cloud minus the PD. The mean cloud is expressed as a fraction, from 0 to 1.0. Contour interval: 0.05, negative contours are dashed and the zero line is bold. 178

7.13 MUGCM annual 850 hPa wind anomaly for MUGCM simulations with (a) full LGM boundary conditions, and (b) full LGM boundary conditions with the SSTs updated in the Australian region. Units: ms$^{-1}$ 179

7.14 MUGCM annual differences in temperature for the full LGM simulation with the SSTs updated in the Australian region and the global CLIMAP SSTs cooled by (a) 1°C and (b) 2°C. Contour interval: 1°C 180
7.15 MUGCM low level cloud anomaly for the full LGM simulation with the SSTs updated in the Australian region and the global CLIMAP SSTs cooled by (a) 1°C and (b) 2°C. The mean cloud is expressed as a fraction, from 0 to 1.0. Contour interval: 0.05, negative contours are dashed and the zero line is bold. 183

7.16 Improved zonal gradient in the Pacific SSTs minus CLIMAP, with updated Australian region. Contour interval: 0.5°C 184

7.17 Annual average anomaly of temperature at the lowest sigma level with improved zonal gradient in the tropical Pacific SSTs, updated Australian region SSTs and all other PMIP boundary conditions. Contour interval: 1°C 184

7.18 Annual 850 hPa zonal wind, zonally averaged from 125 to 145° longitude in ms⁻¹. Simulations include PD, LGM and LGM with the Australian region SSTs updated, and the tropical Pacific SST gradient modified to that suggested by Liu et al. (2000) (PMIP Oz Grad) 186

8.1 Six hourly volumetric soil moisture for June from one year. a) For top 10 cm from NCEP/DOE Reanalyses II (NCEP2), 1995, b) MUGCM, for top 0.5 cm, W_g. Letters A-F refer to a gridpoint from each of the climate regimes across Australia, Figure 6.5 201

8.2 Global wind regimes, using the equation of Fryberger (1979) with 10 m winds from the NCEP/DOE reanalyses II (NCEP2) reanalysis. There are nine categories. Red to orange high energy wind regime, greens mid, blue and purple low. Red = uni-directional, dark-orange = bi-directional and light orange = multi-directional. Pale green = uni-directional to dark for multi. Mid blue = uni-directional, dark blue = bi-directional and purple = multi-directional 203

8.3 Dune orientation from Wasson (1986) (pale arrows), and the seasonal NCEP/DOE reanalyses II (NCEP2) mean wind vector (dark arrows) and mean wind speed, contour interval 1.0 m s⁻¹. (a) January, (b) April, (c) July and (d) October 207

8.4 Dune Orientation (pale arrows) and annual NCEP/DOE reanalyses II (NCEP2) mean wind vector (dark arrows) and mean wind speed, contour interval 1.0 m s⁻¹ 208
8.5 Dune orientation (pale arrows) and seasonal MUGCM PD mean wind vector (dark arrows) and mean wind speed, contour interval $1.0 \text{ m s}^{-1}$. (a) January, (b) April, (c) July and (d) October... 209

8.6 Dune Orientation (pale arrows) and annual MUGCM PD mean wind vector (dark arrows) and mean wind speed, contour interval $1.0 \text{ m s}^{-1}$... 210

8.7 Dune orientation (pale arrows) and seasonal NCEP/DOE reanalyses II (NCEP2) sand shifting resultant (dark arrows) and mean total drift potential, contour interval 10, 32, 100 $\text{m}^3\text{s}^{-3}$. (a) January, (b) April, (c) July and (d) October... 211

8.8 Dune orientation (pale arrows) and seasonal MUGCM PD sand shifting resultant (dark arrows) and mean total drift potential, contour interval 10, 32, 100 $\text{m}^3\text{s}^{-3}$. (a) January, (b) April, (c) July and (d) October... 212

8.9 Dune Orientation (pale arrows) and annual NCEP/DOE reanalyses II (NCEP2) sand shifting resultant (dark arrows) and mean total drift potential, contour interval 23, 86, 312 $\text{m}^3\text{s}^{-3}$... 213

8.10 Dune Orientation (pale arrows) and annual MUGCM PD sand shifting resultant (dark arrows) and mean total drift potential, contour interval 23, 86, 312 $\text{m}^3\text{s}^{-3}$... 214

8.11 Rotation between the mean winds and the sand shifting potential in NCEP2 calculated following Kalma et al.(1988). Negative values are a clockwise rotation from the mean to the sand shifting potential... 216

8.12 Dune orientation (pale arrows) and seasonal MUGCM PD sand shifting resultant including the influence of soil moisture (dark arrows) and corresponding mean total drift potential, contour interval 10, 32, 100 $\text{m}^3\text{s}^{-3}$. (a) January, (b) April, (c) July and (d) October... 218

8.13 Dune Orientation (pale arrows) and annual MUGCM PD sand shifting resultant including the influence of soil moisture (dark arrows) and corresponding mean total drift potential, contour interval 23, 86, 312 $\text{m}^3\text{s}^{-3}$... 219

8.14 Dune orientation (pale arrows) and seasonal MUGCM LGM mean wind vector (dark arrows) and mean wind speed, contour interval $1.0 \text{ m s}^{-1}$. (a) January, (b) April, (c) July and (d) October... 221
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.15</td>
<td>Dune Orientation (pale arrows) and annual MUGCM LGM mean wind vector (dark arrows) and mean wind speed, contour interval 1.0 m s(^{-1})</td>
<td>222</td>
</tr>
<tr>
<td>8.16</td>
<td>Dune orientation (pale arrows) and seasonal MUGCM LGM sand shifting resultant (dark arrows) and mean total drift potential, contour interval 10, 32, 100 m(^3)s(^{-3}). (a) January, (b) April, (c) July and (d) October</td>
<td>223</td>
</tr>
<tr>
<td>8.17</td>
<td>Dune Orientation (pale arrows) and annual MUGCM LGM sand shifting resultant (dark arrows) and mean total drift potential, contour interval 23, 86, 312 m(^3)s(^{-3}).</td>
<td>224</td>
</tr>
<tr>
<td>8.18</td>
<td>LGM minus PD total drift potential, including the influence of soil moisture, from the MUGCM simulations. Contour interval: 20 m(^3)s(^{-3}), negative contours are dashed and the zero contour is bold. Arrows are the dune orientations from Wasson [1986]</td>
<td>225</td>
</tr>
<tr>
<td>8.19</td>
<td>Dune orientation (pale arrows) and seasonal MUGCM LGM sand shifting resultant including the influence of soil moisture (dark arrows) and corresponding mean total drift potential, contour interval 10, 32, 100 m(^3)s(^{-3}). (a) January, (b) April, (c) July and (d) October</td>
<td>226</td>
</tr>
<tr>
<td>8.20</td>
<td>Dune Orientation (pale arrows) and annual MUGCM LGM sand shifting resultant including the influence of soil moisture (dark arrows) and corresponding mean total drift potential, contour interval 23, 86, 312 m(^3)s(^{-3}).</td>
<td>227</td>
</tr>
</tbody>
</table>
List of Tables

2.1 References to proxy evidence for LGM temperature and water availability at various sites. The Map number refers to the location in Figure 2.1. The LGM conditions compared to those of the present day: D = dryer, W = wetter, C = cooler, S = same as present day. Temperature reductions are shown in degrees Centigrade .................................................. 13

2.2 References to dates of dune activity. The Map number refers to the location in Figure 2.6. The details include the ‘dating’ method and the location: ‘Ocean’ means that the dunes are now under the ocean, ‘C’ means radiocarbon dating and ‘L’ means luminescence methods. ka means ‘thousand years ago’ .................................................. 25

4.1 The MUGCM and PMIP model names and institution ................................................. 66

4.2 Resolution of the models. The lowest level is in hPa. Information about the PMIP models is from http://www-lsce.cea.fr/pmip/ ................................................. 67

4.3 Land surface schemes of all models. Information about the PMIP models is from http://www-lsce.cea.fr/pmip/ .................................................. 68

4.4 Annual 2 m air temperature (°C) over all of Australia (PD extent) for all models with PD and fixed SST LGM simulations ................................................. 73

4.5 Summer and Winter 2 m air temperature (°C) over all of Australia (PD extent) for all models with PD and fixed SST LGM simulations ................................................. 74

4.6 Australian annual precipitation for PD, LGM and anomaly (mm day$^{-1}$) .................................................. 83

4.7 Australian Summer and Winter precipitation in mm day$^{-1}$ (present day extent) for MUGCM and each model .................................................. 83
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>PD MUGCM total column moisture over regions of Australia and LGM anomaly. Units: mm</td>
</tr>
<tr>
<td>6.2</td>
<td>Percentage of 6 hourly periods with zero rainfall for each of the six points on Figure 6.5. The names refer to the State in which the point lies</td>
</tr>
<tr>
<td>6.3</td>
<td>Area of the climate regions in Figure 3.15, in units of $\times 10^6$ km$^2$</td>
</tr>
<tr>
<td>6.4</td>
<td>Moisture recycling ratio ($\frac{P_m}{P}$) for the Amazon and Sahel from a tracer in the MUGCM</td>
</tr>
<tr>
<td>6.5</td>
<td>Moisture recycling ratio calculated from data averages from the PD and LGM MUGCM simulation for all Australia and each climate region</td>
</tr>
<tr>
<td>6.6</td>
<td>PD MUGCM evaporation over regions of Australia and LGM anomaly, mm day$^{-1}$</td>
</tr>
<tr>
<td>6.7</td>
<td>PD MUGCM $F^+/A$ for regions of Australia and LGM anomaly, mm day$^{-1}$</td>
</tr>
<tr>
<td>6.8</td>
<td>PD and LGM Moisture recycling ratio ($\frac{P_m}{P}$) for Australia from a tracer in the MUGCM for all Australia and each climate region</td>
</tr>
<tr>
<td>7.1</td>
<td>Annual near surface air temperature over different regions. Control total, and differences from control, °C</td>
</tr>
<tr>
<td>7.2</td>
<td>as Table 7.1 but for JJA</td>
</tr>
<tr>
<td>7.3</td>
<td>as Table 7.1 but for DJF</td>
</tr>
<tr>
<td>7.4</td>
<td>Annual precipitation over different regions with different boundary conditions. Control total, and differences from control, mm/day. Bold numbers are significant differences at the 95% level</td>
</tr>
<tr>
<td>7.5</td>
<td>As Figure 7.4 but for JJA</td>
</tr>
<tr>
<td>7.6</td>
<td>As Figure 7.4 but for DJF</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Background

Ice-cores from Antarctica show large swings in the atmospheric concentration of greenhouse gases and reconstructed temperature over the last 700,000 years (Augustin et al., 2004), with the last 420,000 years showing strong 100,000 year cycles. Each 100,000 year cycle involves long periods of cooling to a maximum glaciation followed by a rapid shift to a short warm period, such as at present. The Last Glacial Maximum (LGM) was the most recent maximum of glaciation, and was the culmination of 100,000 years of cooling. For analysis and dating purposes, the LGM is assumed to be a period of stable climate encompassing the period 23,000 to 19,000 years ago (Mix et al. 2001). However there will be local variations in the timing of the coolest conditions across the globe.

In Australia the climate response at the LGM was more subtle than for the Northern Hemisphere continents, which had large ice-sheets extending across them from high latitudes (Peltier 1994). However, proxy evidence suggests that Australia experienced a substantial cooling, with an annual mean temperature up to 10°C cooler (e.g. Miller et al. 1997). There remain however, inconsistencies in LGM proxy evidence across the continent. For example there is evidence of both high lake levels (e.g. Williams et al. 2001) and lakes that were permanently dry (e.g. Chen et al. 1993). The changes in the circulation are also not clear, with a number of conflicting conceptual models of the circulation presented in the literature (Harrison and Dodson 1993). One of the goals of this thesis is to elucidate these seeming inconsistencies in the proxy evidence and conceptual circulations in the literature.
1. Introduction

The Australian continent extends from the tropics to the mid-latitudes and changes in the climate are driven by a range of factors. A powerful approach to better understand the LGM circulation and how the Australian climate responded to circulation shifts at the LGM is by simulating both the present day and the LGM with a global general circulation model.

1.2 Survey of global modelling studies of the LGM

The LGM has been chosen for closer examination with general circulation models (GCMs) in this study, and in many previous studies, due to the extreme changes from the present day climate, the relatively clear climate record from proxy evidence, and the availability of the digital maps of LGM boundary conditions produced for input into GCMs by the project ‘Climate: Long-range Interpretation, Mapping and Prediction’, termed CLIMAP, (CLIMAP, 1976, 1981).

Some of the earliest GCM studies were carried out with low resolution atmospheric models. Gates (1976) used the Mintz-Arakawa 2-level model with the LGM boundary conditions specified in CLIMAP (1976). A slightly more complex atmospheric GCM was used by Williams et al. (1974) to simulate the ice-age climate with boundary conditions different from CLIMAP (1976), in particular, cooler sea surface temperatures (SSTs). Gates (1976) found cooling and drying across most of the globe compared to the present day, as expected from proxy evidence. The Williams et al. (1974) simulation resulted in even cooler temperatures and lower precipitation than the results of Gates (1976), better matching the proxy evidence. The differences in the results may have been due to differences between the models, including the resolution, and differences in the boundary conditions. The cooler SSTs used by Williams et al. (1974) would likely have produced a cooler response in the atmosphere. Gates (1976) was very keen to address the question of model differences by having many different models produce ice-age simulations with the same ice-age boundary conditions.

After these initial GCM simulations of the LGM which describe the broad scale changes from the present day, GCMs began to be used as a tool to help answer specific questions. For example, Rind and Peteet (1985) compared the
1.2 Survey of global modelling studies of the LGM

regional land surface temperatures simulated with a GCM forced with LGM boundary conditions to the temperatures reconstructed from proxies. They found that the simulated temperatures were in general warmer than the temperatures reconstructed from proxies, particularly in the tropics, where LGM snowlines were much lower. The model was forced with the seasonal SST reconstructions presented in CLIMAP (1981), and Rind and Peteet (1985) conclude that the CLIMAP LGM SSTs are too warm. This has implications for much of the following research that prescribed the CLIMAP (1981) SSTs in their LGM simulations.

The influence that the LGM boundary conditions (such as the SSTs or the changes in the solar input) had on the simulated climate was also tested with GCMs. The response of the Northern Hemisphere monsoons, and related rainfall, was used by Kutzbach and Guetter (1986) as a testing ground for the influence of solar and other boundary condition changes. They state that ‘...the general response of tropical monsoon circulations to the orbitally produced solar radiation changes is much larger than their response to changes of long time-constant glacial-age boundary conditions. The reverse holds in non-tropical latitudes.’ Rind (1987) also tested the influence of each of the LGM boundary conditions, by introducing them to the simulation of the present day in turn. The CLIMAP (1981) SSTs, the ice in the regions suggested by reconstructions of LGM ice sheet extent, and the increased height associated with those ice sheets, all produced strong responses. The responses were not necessarily of the same sign, and they cancelled each other out to some extent. In comparing his results with earlier studies and proxy evidence Rind (1987) found that many of the earlier studies produced results more in line with the proxy evidence, most likely because they were using SSTs that were cooler than those of the CLIMAP (1981) reconstruction.

The extreme conditions at the LGM compared to the present day provide an excellent environment in which to test the response of the simulations to changes within the model, including the model resolution. To assess the influence of the model resolution on simulations of the present day and ice age climate, Rind (1988) used two different GCM resolutions, 8°x 10° and 4°x 5° latitude and longitude. He found that the model with the finer grid had a stronger response to the ice age boundary conditions, with a larger reduction in the hydrologic response and greater decrease in temperature, and the increase in eddy transport became more pronounced.
As model resolution improved, studies of the response in smaller regions were considered more reliable. Smith (1989) used the Melbourne University GCM (MUGCM) at 3.3° by 5.6°, a higher resolution than those used by Rind and Peteet (1985) or Kutzbach and Guetter (1986), and concentrated on the Australian region. The LGM July temperature over Australia was simulated as being cooler than the present day, and the mean westerly wind in the south of the continent decreased in strength. The changes in precipitation totals across the continent were noisy.

Researchers began to implement new components into their GCMs that could be compared directly to proxy evidence. Joussaume (1990) included dust transport in a GCM and then simulated the LGM to test the increased dust levels found in ice cores at the LGM (Joussaume, 1993). Another important tracer implemented into GCMs used for paleoclimate studies was the isotopes of water including the varying fractionation levels for the different isotopes (e.g. Joussaume et al. (1984); Joussaume and Jouzel (1993); Mathieu et al. (2002); Noone and Simmonds (2002)).

It was obvious that the worth of paleoclimate modelling was being recognised.

1.3 Paleoclimate Modelling Intercomparison Project (PMIP)

As the models improved and the questions they were being utilised to answer broadened, a major modelling initiative began that extended the scope of paleoclimate modelling. This was the Paleoclimate Modelling Intercomparison Project (PMIP). The history that led to the PMIP is outlined below.

Many climate research groups developed their own GCM through the 1980s, and by the early 1990s a project was established to compare GCM results from simulations with the same present day boundary conditions: the Atmospheric Model Intercomparison Project (AMIP) (Gates, 1992). This brought to fruition the suggestion for a model intercomparison made by Gates (1976). In AMIP, the monthly sea surface temperature (SST) and sea-ice were prescribed for the years 1979 to 1988. Once the computational stage was finished in 1993 a range of diagnostic subprojects were devised. In the first international AMIP conference, a proposal was made by Sylvie Joussaume (Joussaume and Taylor, 1995) for an
intercomparison project similar to AMIP for simulations of past climates. This subproject was the beginning of the Paleoclimate Modelling Intercomparison Project (PMIP).

Whilst the AMIP examined the impact of changes in modern day boundary conditions, the PMIP used different models to examine their capabilities and differences in simulating past climates. The PMIP proposed simulations for the present day and two times in the past. These were the two most recent periods of peaks in the global climate system - the Climatic Optimum, 6000 years ago, believed to be warmer than today, and the Last Glacial Maximum, 21,000 years ago, believed to be much cooler. For the LGM simulation, the SST, sea-ice and also the extensive Northern Hemisphere ice sheets were prescribed. The results from nine models were compared for this part of the project.

The different models produced a range of results for a particular area of study. This range will provide an ‘error-bar’ due to model differences, which, when compared with proxy reconstructions and their errors, will allow for a clearer comparison (Kageyama et al., 2001). The range of results due to model differences can also be used as a benchmark against which to assess a new model. From a modelling perspective, the range of model results will also help to highlight differences due to model resolution or parameterisations.

A large number of studies have used PMIP results for examining the responses at the LGM for a range of different aspects of the climate. These include studies of the changes in the mid-latitude large scale circulation in the Northern Hemisphere (Hall et al., 1996; Kageyama et al., 1999a,b; Dong and Valdes, 2000), studies of the African monsoon at the LGM (Braconnot et al., 1999; Joussaume et al., 2000), a study of the LGM climate over Europe and western Siberia (Kageyama et al., 2001), and a test of the model veracity over South America (Valdes, 2000). However, there has been very little analysis of GCM LGM output in the Australian region, or indeed, the Southern Hemisphere.

A good deal of the energy in many of the modelling groups involved in the PMIP is now directed towards producing simulations of past climates with coupled GCMs (Harrison et al., 2002). The spin-up time for ocean GCMs is much greater than for the atmosphere, as the response to forcing is slower to reach equilibrium. The LGM ocean will take a particularly long time to spin up as it must find an equilibrium quite distinct from that of the initial conditions (the present day ocean). The guidelines for this next stage have now been set.
This is a very exciting new project, but there are still many questions that have not been answered with the results of the PMIP with atmospheric GCMs, particularly in the Southern Hemisphere.

1.4 Aims of this thesis

It is clear that there is a need for a detailed analysis of the Australian weather and climate at the LGM, as simulated by GCMs. This thesis aims to undertake this further analysis in three ways, outlined below.

Firstly, as mentioned above, the Australian climate response at the LGM is more subtle than other regions of the globe, and there are a number of drivers of Australia’s different climate regimes. This thesis will examine the range of responses of the models involved in PMIP over Australia and hence will help provide an understanding of the limitations on simulating Australia’s climate under LGM conditions with models of this nature, and how the model resolution and surface schemes affect that.

Secondly, aspects of the LGM boundary conditions are extremely different from the external drivers of today’s climate. This thesis aims to determine the sensitivity of Australia’s climate to the changes in these boundary conditions. This will help better understand the drivers of Australia’s climate both at the LGM and at the present day.

Finally, this thesis aims to compare the GCM output with proxy evidence, to both ‘ground-truth’ the GCM results and, where the proxy interpretations vary from each other, provide a consistent climate to help better understand the range of interpretations of the proxy evidence.

By achieving these aims, this thesis will not only further our understanding of the mechanisms driving Australia’s climate, both now and in the past, but will also contribute to the global understanding of the LGM.

1.5 Outline

A broad outline of the literature on proxy evidence for changes in the moisture availability, temperature and circulation in the Australian region is presented in Chapter 2.

In this study the results from a number of GCMs will be presented. For in-depth analysis, a number of simulations have been run using the Melbourne Uni-
versity GCM (MUGCM). Chapter 3 describes the MUGCM along with methods implemented to better examine dune movement, a key proxy used to estimate past winds. The present day data used for reference are also described in this chapter, as are the boundary conditions for the present day simulations and the LGM. A brief comparison is made between the mean MUGCM results and data.

The simulated fundamental near-surface climate variables (temperature and precipitation) from the models included in the international paleoclimate modelling intercomparison project (PMIP) and MUGCM are shown in Chapter 4. A discussion on how model resolution and parameterisation has a bearing on the results is included.

To assess changes in the circulation and the storms crossing southern Australia, high frequency data is required. The MUGCM is used to describe a number of methods of determining the storm regions and their changes between the present day and LGM simulations in Chapter 5.

Changes in aspects of the hydrological cycle are explored in Chapter 6. The global average of cooler and drier conditions will modify the atmospheric water vapour signature, and this is compared across PMIP simulations. Over Australia the balance of evaporation, precipitation and the degree of local land surface influence on these will be considered.

The LGM climate is so extreme in relation to the present day that the drivers of changes can be determined by introducing each LGM boundary condition into the present day simulation in turn. The results of these sensitivity tests is described in Chapter 7. An examination on how changes in the boundary conditions can also alter Australia’s climate follows.

Chapter 8 compares the proxy dune evidence with present day data and the winds from the MUGCM. The limiting factors of the wind strength and soil moisture are then included to determine the degree of change in orientation between the mean wind and the potential for sand movement.

The thesis conclusions will be summarised in Chapter 9.
Chapter 2

Proxy evidence of the Australian climate at the LGM

The aim of this chapter is to gain an appreciation for the circulation and climate conditions at the LGM as shown by proxy evidence in the literature. A review of the reconstructed temperature and precipitation changes across Australia will be presented first, followed by an outline of the orientation and age of proxies for the wind.

Throughout the paleoclimate literature there are many interpretations of proxy evidence that suggest that the climate of Australia at the LGM was cooler, drier and possibly windier. Most of the evidence is from lake levels, fossil pollen, periglacial and geomorphological features. Review papers compiling LGM data from various sites, and in some cases describing possible LGM circulation, include Galloway (1965), Bowler et al. (1976), Webster and Streten (1978), Chappell and Grindrod (1983), Bowler (1986), Chappell (1991), Wasson and Donnelly (1991), Hubbard (1995a), Allan and Lindesay (1998), Farrera et al. (1999), Hunt and Barrows (1999), Kershaw et al. (2000), Williams (2000), and Berry (2001).

Historical dates can be referred to in a number of different ways. This thesis endeavours to use only calendar dates, with years ago referring to the reference time of 1950. 1950 is traditionally used as a reference date for the present day since the atmospheric ratio of radioactive carbon to stable carbon was modified greatly after this date by nuclear tests. In some cases it is not made clear in the literature whether the age of the evidence is dated using calendar dates or dates derived from radiocarbon methods. At the LGM these diverge by 3000 years, (Stuiver et al. 1998), thus the LGM has been referred to as being at
18,000 or 21,000 years ago. Radiocarbon dates will be referred to with a $^{14}$C after the date. Some of the data presumed to be LGM is only presumed to be so because it formed in a very cold environment, and thus the dates have not been anchored with direct dating techniques.

2.1 Reconstruction of Australia’s LGM temperature and precipitation from proxies

Surface temperature change can be due to changes in the vertical column radiative balance, atmospheric composition or changes in the circulation. The amount and spatial distribution of precipitation are intimately tied to the changes in the circulation. Thus, an appreciation of the LGM precipitation and temperature will also provide insight into the how the LGM circulation was different to today. There is a whole range of evidence suggesting shifts in the precipitation and temperature, some of which will be described here.

The interpretation of the climate from proxy evidence is often from the moisture balance available to a surface system, for example a lake or the types of pollen in a core. The amount of water available to the system is affected by temperature and evaporation as well as precipitation. Thus it is sometimes not clear if the changes seen are due simply to changes in precipitation, or if there is also a signal of temperature and wind. Most authors of the literature cited here attempt to untangle the signals. In this section the interpretation of changes in temperature and the availability of moisture will be considered.

There are limitations on the accuracy of detecting climate signals in all proxy measures. Those associated with fossil pollen are presented here.

Problems with using pollen as a proxy for climate

The sediment cores from which pollen sequences are taken often show clear layering that allows tighter chronological bounds on dates than some other proxy measures such as geomorphological features. However, the interpretations to be made from the extent and type of vegetation evident from fossil pollen suffers from a range of problems.

Changes in the vegetation are taken to mean changes in the precipitation or temperature regime as reconstructed from modern analogues. This is reasonable in terms of the time frame of evolution, but the many aspects of veg-
2.1 Reconstruction of Australia’s LGM temperature and precipitation from proxies

Plant communities will interact under the present climate conditions and finding a community with a different composition at the LGM will not necessarily give a clear indication of the changes in climate. Henry Nix, among others, has developed BIOCLIM [http://cres.anu.edu.au/outputs/anuclim/doc/bioclim.html], a system that determines the major climate controls, such as precipitation or radiation, on a number of plant species today. Pickett et al. (2004) also determined climate conditions for present day pollen across Australia using many samples at many sites. Pickett et al. (2004) then applied these climate regimes to the LGM pollen distribution and found that LGM conditions were drier and probably cooler. These studies allow some confidence in the reconstruction of climate from fossil pollen, given the good understanding of the modern analogues used, however, there are other considerations for reconstructing the climate from evidence of LGM plant communities.

The LGM atmospheric carbon dioxide concentration was less than two thirds of the Present Day (PD) concentration (Barnola, 1987). Low levels of atmospheric carbon dioxide stress vegetation, in some cases giving a similar signal to a decrease in temperature or precipitation (Cowling, 1999; Berry, 2001). As carbon dioxide increases at present, it acts as a fertiliser and is expected to do so until plant growth is limited by available nutrients (Dodson, pers. comm. 2004), which may modify the global carbon budget over time (House et al., 2003). Thus a reconstruction of climates from pollen abundances must take the changes expected just from the decreased carbon dioxide concentration into account.

Vegetation is also affected by fire. Fire was used by early Australians to encourage grasslands to provide pasture for the grazing animals that they ate. Evidence of early habitation is linked to changes in the vegetation caused by fire-stick farming (Ross et al., 1992). In the north of Australia there is evidence of human habitation from about 60,000 years ago (Roberts et al., 1990, 1994). Across the rest of the continent, evidence of human occupation has been found in southwestern Australia at 48,000 years ago, (Turney et al., 2001), and dates for the burial of human skeletons in southeastern Australia have been dated at about 40,000 years ago, although humans are thought to have been in the area from between 46,000 and 50,000 years ago (Bowler et al., 2003). It is possible that the human population number and extent was increasing from 50,000 years ago to the LGM, with an accompanying increase in fire-stick farming, perhaps
leading to the evidence of grasslands where once there was forest, as suggested by Luly (2001).

Thus, although there is a reasonable understanding of the climates in which a range of Australian vegetation currently grows, and the abundance and distribution of LGM pollen might be an accurate measure of the corresponding PD environment, the LGM environment may have had different pressures from the atmospheric carbon dioxide levels and human activity.

Figure 2.1: Location of LGM paleo proxy evidence of local water availability and temperature. Each number refers to reference locations in Table 2.1. Changes in available moisture are to the left of the number, (D=dryer at the LGM, W=wetter), temperature changes to the right, (C=cooler). Number 11 refers to three locations. Topography shading: -120, 200, 400, 800 m. The region shown by grey shading is the approximate land extent at the LGM. Topography data is from ETOPO5 database.
## 2.1 Reconstruction of Australia’s LGM temperature and precipitation from proxies

The LGM conditions compared to those of the present day: D = dryer, W = wetter, C = cooler, S = same as present day. Temperature reductions are shown in degrees Centigrade.

<table>
<thead>
<tr>
<th>Map</th>
<th>Reference</th>
<th>Description</th>
<th>LGM cf PD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Torgersen et al. (1988)</td>
<td>grassland, Carpentaria</td>
<td>D</td>
</tr>
<tr>
<td>1</td>
<td>Torgersen et al. (1985)</td>
<td>pollen</td>
<td>D</td>
</tr>
<tr>
<td>1</td>
<td>Chivas et al. (2001)</td>
<td>multi-proxy</td>
<td>D</td>
</tr>
<tr>
<td>2</td>
<td>Kershaw (1986)</td>
<td>pollen</td>
<td>D</td>
</tr>
<tr>
<td>3</td>
<td>Bowler (1983)</td>
<td>dunes on lake bed</td>
<td>D</td>
</tr>
<tr>
<td>4</td>
<td>Wyrwoll and Miller (2001)</td>
<td>paleosol, Lake Gregory</td>
<td>D</td>
</tr>
<tr>
<td>4</td>
<td>Bowler et al. (2001)</td>
<td>dunes at lake edge</td>
<td>D</td>
</tr>
<tr>
<td>5</td>
<td>English et al. (2001)</td>
<td>aeolian activity at Lake Lewis</td>
<td>D</td>
</tr>
<tr>
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<td>Chen et al. (1993)</td>
<td>dune formation on Lake Amadeus</td>
<td>D</td>
</tr>
<tr>
<td>7</td>
<td>Miller et al. (1997)</td>
<td>egg shell from Lake Eyre</td>
<td>-9°</td>
</tr>
<tr>
<td>7</td>
<td>Nanson et al. (1998)</td>
<td>beach ridges</td>
<td>W</td>
</tr>
<tr>
<td>8</td>
<td>Martin (1973)</td>
<td>vegetation shift south</td>
<td>D</td>
</tr>
<tr>
<td>9</td>
<td>Williams et al. (2001)</td>
<td>Still water, Flinders Ranges</td>
<td>D, C</td>
</tr>
<tr>
<td>10</td>
<td>Bowler et al. (1986)</td>
<td>deflation from Lake Frome</td>
<td>D</td>
</tr>
<tr>
<td>10</td>
<td>Singh and Luly (1991)</td>
<td>pollen, Lake Frome</td>
<td>D</td>
</tr>
<tr>
<td>11</td>
<td>Cupper (2003)</td>
<td>dry playa, Darling anabranch</td>
<td>D</td>
</tr>
<tr>
<td>11</td>
<td>Miller et al. (1997)</td>
<td>drying at Willandra Lakes</td>
<td>D</td>
</tr>
<tr>
<td>12</td>
<td>Wasson (1984)</td>
<td>fish remains at Kangaroo Lake</td>
<td>W</td>
</tr>
<tr>
<td>12</td>
<td>Pickett (1997)</td>
<td>dune activity, south west WA</td>
<td>D</td>
</tr>
<tr>
<td>13</td>
<td>Barrows et al. (2001)</td>
<td>pollen changes indicate drier vegetation</td>
<td>D</td>
</tr>
<tr>
<td>13</td>
<td>Galloway (1965)</td>
<td>glacial advances, Main Range</td>
<td>C</td>
</tr>
<tr>
<td>13</td>
<td>Singh (1983)</td>
<td>periglacial features, pollen</td>
<td>D, -6-10°</td>
</tr>
<tr>
<td>14</td>
<td>Galloway (1965)</td>
<td>High lake levels, Lake George</td>
<td>W, C</td>
</tr>
<tr>
<td>14</td>
<td>Bowler et al. (1976)</td>
<td>pollen, Lake George</td>
<td>D</td>
</tr>
<tr>
<td>15</td>
<td>Stone, (pers. comm. 2003)</td>
<td>Lakes more full than at present</td>
<td>W</td>
</tr>
<tr>
<td>16</td>
<td>Bowler et al. (1976)</td>
<td>soil on floor of Lake Keilambete</td>
<td>D</td>
</tr>
<tr>
<td>17</td>
<td>Bowler et al. (1976)</td>
<td>lower snowline, Tasmania</td>
<td>S, -6-10°</td>
</tr>
<tr>
<td>17</td>
<td>Colhoun (1985)</td>
<td>maximum glacier extent</td>
<td>-6.5°</td>
</tr>
</tbody>
</table>

Table 2.1: References to proxy evidence for LGM temperature and water availability at various sites. The Map number refers to the location in Figure 2.1.
2.2 Proxy evidence of temperature and water availability

The following sections are ordered by geographical location. Evidence from the literature is noted on the map in Figure 2.1. As each site is first mentioned, a bracketed figure will appear in the text that will correspond to the numbers on Figure 2.1 and Table 2.1. The water availability is a measure of the moisture available in the environment in which the proxy evidence is found, such as reflected by pollen, lake levels and dunes. In most cases the water available to surface systems is a good estimate of the precipitation, but local changes can have strong implications for how precipitation levels are expressed. For example, changes in the flow of river systems or pressures from humans.

2.2.1 North Australia

The majority of precipitation in the north of Australia is associated with the summer monsoon. The wet season in the north of Australia derives from three parts of the Australian monsoon. From the east comes the ‘quasi-monsoon’ with the trade winds, and from the west the ‘pseudo-monsoon’, (Figure 25 of Gentilli (1971)). The component from the north is the ‘true’ monsoon. The interaction between the flow from the north and the others helps to produce the ‘monsoon convergence line’, where the potential for convection and storms is greatly enhanced. Heat lows are the major driving force of the Australian summer monsoon. Commonly these form over the Pilbara and Cloncurry regions in the northwest and northeast of Australia respectively. The tradewinds in the east bring a steady stream of moisture onto the east coast, with orographic rainfall along the Great Dividing Range, which can occur year round. In the west, the northward circulation from the high in the Indian Ocean is diverted across northwest Australia in response to the heat low.

At the LGM, given the sea-level drop of approximately 120 m (Yokoyama et al., 2000, 2001a), the Gulf of Carpentaria (1) and Joseph Bonaparte Gulf, to the north of Australia, were exposed as land (Yokoyama et al., 2001b). This newly exposed land would have the greatest influence on the signature of the flow associated with the ‘true’ monsoon. The extended land might also alter the location of the heat-lows, changing the paths of the monsoon, and slow the near surface winds due to increased surface friction. If the ‘true’ monsoon was
less vigorous, there would be limited low level convergence along the monsoon convergence line and less propensity for convective storms.

The extended land would also decrease the potential moisture source to the flow, although this might be tempered by the large lake in the present Gulf of Carpentaria, known at the LGM as Lake Carpentaria (1) (Yokoyama et al. 2001b). Tropical cyclones would be likely to make landfall on the exposed land before reaching the present day land extent, regionally shifting their influence, although De Deckker (2004) found that there was no evidence of disturbance by tropical cyclones in Lake Carpentaria. The vegetation around Lake Carpentaria was grassland at the LGM, (Torgersen et al. 1985, 1988; Chivas et al. 2001), which they suggest indicates drier LGM conditions in this region.

Fossil pollen data from the northeast coast of Queensland, (2), show a sharp change from rainforest to open woodland (Kershaw 1994). Kershaw (1994) suggests the sharp change to be strongly driven by increased vegetation burning by humans rather than climatic effects. The present day tradewinds that bring the moisture to the north east of Australia are a robust feature that would be expected to have been present at the LGM. However, their climatological orientation near the east coast might have been different and they may have been less vigorous due to a weakened LGM Walker circulation. The LGM climate has been described as being more ‘El Niño-like’ from new ocean cores, (Beaufort et al. 2001; Müller and Hope 2004), which would suggest a weakened Walker circulation, while Ayliffe et al. (1998) linked precipitation variability at Naracoorte in southeast Australia to changes in the Walker circulation strength, with a weaker circulation at the LGM. An earlier study by Kershaw (1986) suggested that there is evidence of drier conditions at the LGM, with the water available to plants (usable precipitation) only 40% of that of today. Allowing for the problems with reconstructions of precipitation from pollen, this result may be considered less reliable. However the percentage change is large, and evidence from oceanic cores concur.

At Lake Woods in the Northern Territory (3) there are now relict dunes on the bed of an old mega lake (Bowler 1983). The timing of dune activity is associated with the low sea-level of the LGM and the same dune building period that created the submerged dunes on the northwest coast (Jennings, 1975).

Lake Gregory, Western Australia (4) is a fresh to brackish lake that is usually full, and lies on the edge of the present day monsoon extent. It was a larger lake at about 300,000 years ago, contracting to a final ‘mega-lake’ phase at 120,000
years ago (Bowler et al., 2001). During the LGM there is no lake activity recorded (Bowler et al., 2001), indicating conditions drier than those of today. Wyrwoll and Miller (2001) found evidence of an established soil layer under a relatively thin layer of sediment near Lake Gregory. Although this soil layer was not dated, they suggested that it was from an extended dry period during the LGM.

Across northern Australia, a region where the hydrology is strongly influenced by the monsoon, the evidence suggests drier conditions at the LGM.

### 2.2.2 Central Australia

Central Australia, to the west of the Great Dividing Range, has highly variable rainfall in the present day, with reasonably low mean values (typically less than 300 to 400 mm per year). It is generally under the influence of the subtropical ridge. The majority of rainfall in this region is from monsoonal incursions or the remnants of tropical cyclones. Some rainfall is from frontal systems to the south that extend into the lower latitudes, sometimes combining with moisture sources from cloud bands extending from low latitudes, termed ‘north west cloud bands’, as described in Wright (1988).

English et al. (2001) examined shore line dunes around Lake Lewis (5), and found that aeolian activity was common throughout the LGM, with little evidence of flooding. The hydrological conditions over a large area are reflected by conditions at Lake Lewis due to its large catchment. Since the LGM, floods have occurred sporadically, and conditions have not been as dry as at the LGM.

The stratigraphy in cores from Lake Amadeus (6) studied by Chen et al. (1993), revealed a time when dunes formed on the lake floor, indicating a very dry period. Chen et al. (1993) linked this period of dune building with the timing of dry lakes in southeast Australia at about 25,000 to 16,000 years ago.

Lake Eyre (7) has been the site of many studies on the hydrology and temperature of the LGM. Part of the fascination of this area is that Lake Eyre itself is large, and forms the terminus of a huge internal basin, extending across one sixth of the Australian continent. The Lake Eyre basin extends across a number of climatic zones. Hope et al. (2004) provides a description of the physical environment, surrounding climate and inflow regime to Lake Eyre. In the north, rivers rise in the monsoonal regions, while in the south the lake and rivers to its west derive sporadic rain from both the systems embedded in the westerlies
and incursions of systems from the north, \cite{Kotwicki1986}.

\cite{Miller1997} examined the paleo-temperature using the amino-acid racemization in ancient egg-shells collected from the Madigan Gulf of Lake Eyre. They found LGM mean temperatures up to 10°C cooler than the present day. The temperature reduction they found is large, but, given the small errors in the amino-acid racemization method, Magee \cite{Magee2000} is confident that the temperature reductions shown with this method accurately reflect a much cooler environment at the LGM. \cite{Miller1997} also found reductions in temperature of the same magnitude at Lake Victoria, in the south west corner of New South Wales, and at Lake Mungo, 150 km north east from Lake Victoria.

Evidence of LGM aridity around Lake Eyre has been found by \cite{Nanson1992}, \cite{Croke1996}, \cite{Magee1998}, \cite{Croke1998} and \cite{Magee2004}. An alternative situation was suggested by \cite{Nanson1998}, who note evidence of high lake levels in salt lakes near Lake Eyre at the LGM. The dates they obtain from beach ridges formed via wave action at that time are around 22,000 and 26,000 years ago. They attribute these higher lake levels to occasional flooding from monsoonal storms, and lowered evaporation levels.

Further west, at Eucla, near the West Australian border with South Australia near the present day coast, \cite{Martin1973} found that the Mallee scrub present today was absent at the LGM. Along with the lack of trees there was also less evidence of habitation at this time. \cite{Martin1973} believed that human habitation was moved further south, to the 160 km or so of land exposed with the lowered sea-level, which was vegetated. She suggests that the rainfall isohyets had shifted south along with the continental extent.

At Brachina Gorge in the Flinders Ranges (southern South Australia) \cite{Williams2001} there is evidence of fine sediments extending either side of the river course that is ephemeral today \cite{Williams2001}. In the current climate regime the river is generally dry, with occasional large floods that transport large rocks. To accumulate fine sediment, there must have been gently flowing water, uninterrupted by the large floods that occur today. \cite{Cock1999} has interpreted the evidence as showing the presence of a lake, caused by a damming of the gorge. This new blockage combined with lowered evaporation levels caused the lake to survive through the LGM. \cite{Williams2001}, on the other hand, suggested that a large wetland explains the evidence better. Either way, a strong change in the circulation and hydrology is suggested, with few, if any of
the monsoonal incursions that dominate the region today.

To the east of the Flinders Ranges cores from Lake Frome (10) have revealed evidence of deflation from the lake bed at the LGM \cite{Bowler et al. 1986}. The chronological sequence from this sediment core is reasonably well dated. Pollen from the same sequence shows changes in the structure of the vegetation, possibly linked to climate change as discussed in \cite{Singh and Luly 1991}, although \cite{Luly 2001} suggests that other factors such as human occupation may have had an influence on these changes.

At the southeastern extent of the semi arid zone, \cite{Cupper 2003} found that playas (flat, shallow, undrained desert basins that at times become a shallow lake) in the southwestern corner of New South Wales (11) had falling water levels and increasing incidence of wind deflation. Dunes formed from this deflation were dated as 20,000 years old. His results suggest that the LGM was dry and windy period in this location.

The lunette dunes around the now dry and vegetated Willandra lakes (11) have been studied extensively, \cite[e.g. ]{Bowler et al. 1976}. Carbon dates reveal that a significant phase of drying began around 26,000 \textsuperscript{14}C years ago and continued through to 15,000 \textsuperscript{14}C with a brief period of high levels at 18,000 \textsuperscript{14}C. There is also evidence of longitudinal dune activity in this region at the LGM. Details about the Australian dunefields will be discussed further in Chapter 8.

Lake Mulurulu, in the Willandra lakes system, floods occasionally in the present day, thus a period when this lake did not flood at all and the linear dunes were active was most likely drier than the climate today.

On the map of temperature and water availability changes in CLIMANZ I, \cite{Chappell and Grindrod 1983}, there is one point in south eastern Australia with wetter conditions shown. This is from evidence of fish remains at Kangaroo Lake (11) at the LGM \cite{Hope 1983b}. At present the lake is often full \cite{Cupper, pers. comm.}, and thus fish remains may well be found under present conditions. Given the temperature depression reconstructed relatively nearby \cite{Miller et al. 1997, Barrows et al. 2001}, there were likely cooler temperatures in this region at the LGM. Following similar thinking to that of \cite{Williams et al. 2001}, lower temperatures might result in lower potential evaporation and longer high water stands even with a reduction in precipitation. Thus this ‘W’ on the map does not necessarily signify an increase in rainfall.
2.2 Proxy evidence of temperature and water availability

2.2.3 South western Australia

South western Western Australia (12) has a climate quite distinct from its surrounding regions in the present day. It currently receives an annual average rainfall of about 800 mm, most of which falls in winter. To the north and inland from south west Western Australia the climate is under the influence of the subtropical high, and hence rainfall is usually extremely low, with rainfall from the occasional monsoonal incursion, remnants of a tropical cyclone, or north west cloud band.

The warm Leeuwin Current that runs close to the western Australian shore was shown to be weaker at the LGM, and possibly did not extend as far south as it does today (Martinez et al., 1999). Cooler waters off the coast may reduce the moisture content of the air, leading to less potential for precipitation.

There is evidence of drier conditions at the LGM in the southwest. For example, LGM dune activity was evident in the region (Wasson, 1984), indicating less vegetation cover. The comprehensive study of Pickett (1997) showed a shift in vegetation type from that of today to a vegetation more common in drier conditions from 20,000 to 11,000 years ago in the three locations she considered on the Swan Plain. The fossil vegetation remains suggest that the driest conditions were after the LGM, in line with other studies that suggest that this was due to increased demands by vegetation for water due to the warming temperatures. The references cited by Wyrwoll et al. (2000) also suggest a decrease in precipitation at the LGM compared to the present.

2.2.4 South eastern mainland Australia

The coastal regions of south east mainland Australia have an even seasonal rainfall distribution in the present day and support permanent rivers and forests. The south western parts of Victoria receive most of their rain in winter, while summer rain becomes important northward on the east coast.

There is no permanent snow or glaciers anywhere on mainland Australia at present, though there are regions that receive snow in most years. One such region is the Great Dividing Range in Australia’s south east (13). The vegetation in these regions is distinctly alpine, with snow gums and, higher up, treeless alpine heath. Much of the early work analysing past alpine climate, as reviewed by Bowler et al. (1976), uses periglacial features, pollen and one radio-carbon date of maximum glacial extent less than 20,200 $^{14}$C years ago.
From the periglacial evidence the range of suggested temperature depression was from 6 to 10°C below present day temperatures. Although the treeline was lower, the impact from the glacial features was small and there was also believed to be reduced precipitation in this region during the LGM. Barrows et al. (2001) discusses glacial advances in the Mt. Kosciuszko region (13), one of which occurred 19,100 years ago (with an error of 1600 years). This is one of a series of glacial advances in the region, with decreasing intensity from the first which occurred about 60,000 years ago, to the last rapid ice retreat at about 15,900 years ago. For glaciers to persist the temperatures must have been cooler than the present day.

Lake George in NSW (14) is a semi-ephemeral brackish lake. The catchment of Lake George includes periglacial features from the LGM. The general consensus is that the LGM temperature was colder than today, with estimates of the cooling in the order of at least 8°C. Galloway (1965) Singh et al. (1981) Singh (1983). Singh (1983) estimated this from shifts in the presence of different pollen types, which indicate a lowering of the line above which there are no trees by 1200-1500m. Bowler et al. (1976) suggests that prior to 22,000 14C years ago, the water level at Lake George was the same as today, with forest at its edge. More recently than 22,000 14C years ago the lake level was lower and the vegetation was no longer forest.

Evidence from fossil pollen in the Australian mainland’s south east shows a lowering of the alpine tree line, and a general reduction in forest cover. A reduction in forest cover in catchments leads to increased runoff if there is no change in the rainfall. Increased snowfall will increase the spring run-off. An increase in river discharge will also be reflected in the levels of lakes in the upper reaches of such catchments. Nanson et al. (1998) shows that Lake Urana, near Jerilderie, has a well dated high level stand at the LGM. Lake Nekeeya in the Grampians was also shown to have high levels at the LGM, with similar reasoning. (Bowler, pers comm 2002). Further north, the lakes Little Kanyapella and Old Lake Barmah, near Echuca (15), show evidence of being wet at the LGM (Stone, pers comm 2002). With the potential for increases in runoff, and decreases in evaporation, these high lake levels may not indicate more rainfall.

Closed lakes with small catchments provide a useful estimate of the precipitation and evaporation balance in the area local to the lake. There are several of these in western Victoria (16), providing a good record of the Holocene and
2.3 Paleo-circulation from proxies

the time just before European settlement, \cite{Jones et al. 2001}. This record is consistent between the different lakes. Studies cited by \cite{Bowler et al. 1976} found evidence of soil formation on the floor of Lake Keilembete between about 18,000 $^{14}$C and 10,000 $^{14}$C years ago, indicating dry conditions. As at Eucla, near the coast on the Western Australia/South Australia border, this drying may be due to a circulation shift brought about by the coastline shifting far further south, \cite{Martin 1973}.

2.2.5 Tasmania

Tasmania (17) is further south than mainland Australia, positioned well within the present day westerlies. Tasmania’s continentality increased at the LGM as Bass Strait became a land bridge. \cite{Colhoun 1983} describes decreases in temperature of the order of that reconstructed on the mainland (6-10$^\circ$C), from a range of evidence, including shifts in the vegetation and periglacial features. A decrease in the precipitation is also strongly inferred from this evidence. \cite{Colhoun 1985} put the temperature depression of the last glacial expression in Tasmania, which was at a maximum at 18,800 $^{14}$C years ago, at 6.5$^\circ$C. The dating of the glacial extreme is from organic material in an end moraine (17). \cite{Barrows et al. 2002} found glaciation on the Tasmanian central plateau and West Coast Ranges at 20-17,000 years ago, where there is no permanent snow today, again suggesting much cooler temperatures in Tasmania at the LGM.

2.3 Paleo-circulation from proxies

There are a number of different proxy measures of the large-scale circulation and its changes. Marine cores can provide evidence of changes in upwelling and sea surface temperatures that can indicate shifts in the wind stresses affecting the ocean \cite{Barrows et al. 2000, Li 2004}. Fine particles from the land found in marine cores can also provide information about the conditions aloft, if the region of provenance can be determined \cite{Shulmeister et al. 2004}.

The most relevant and well-studied wind proxy for the dry landscape of Australia are dunes. Dunes form a common feature across much of the Australian continent. Many of the inland dunes are believed to have formed thousands of years ago, and may provide information about the near surface wind regime under which they formed. As will be discussed later, the orientation of the dunes
and the near surface winds are linked in non-linear ways, and the relationship is also influenced by a number of other factors.

Jennings (1968) used National Mapping maps based on aerial photographs to describe the direction and extent of the continental dunes across Australia, and identified an anticyclonic whorl, centred approximately along 26°S (Figure 2.2). Figures 2.3(a) and 2.3(b) show lines along the orientation of Australia’s ancient linear and lunette dunes, from Sprigg (1982). Wasson et al. (1988) studied aerial photographs and derived Australia-wide maps of dune type and spacing as well as general direction.

Figure 2.2: Dune orientation on the Australian landscape - from Jennings (1968)

Many authors have mentioned the continent-wide ‘whorl’ of dunes identified by Jennings (1968), often suggesting that it resembles the mean winter anticyclonic atmospheric circulation across the Australian landscape, (Jennings, 1968; Bowler, 1970; Sprigg, 1979; Firman, 1982; Sprigg, 1982; Bowler and Wasson, 1984; Wasson, 1984). Many of these authors believed that the mean present day (PD) winter winds, shifted north by a few degrees of latitude, match this continent-wide ‘circulation’. After careful analysis of the winds at meteorological stations near the dunefields of central Australia, Brookfield (1970) found that it is unlikely that the dunes are the result of a continuous anticyclonic
2.3 Paleo-circulation from proxies

Figure 2.3: Paleo dunes, (a) and lunettes, (b) and their direction and present day sand drifts, (c) and their direction (from Sprigg (1982))

winter system, as it is the summer winds that are stronger and more conducive to sand movement than the winter situation.

To appreciate what the orientation of dunes can tell us about the wind, it is important to understand the different types, and how they generally align to the sand-shifting winds. There are many different dune forms; in Australia, lunette, parabolic and linear dunes types are dominant. Lunettes are transverse crescentic dunes that form around the curve of the downwind shore of some of Australia’s inland lakes. Parabolic dunes build in the presence of vegetation, adjacent to a sediment source, usually sandy channels. From the parabolic dune curve, linear dunes may develop. The most common form of dune in Australia is low linear dunes that extend downwind. Both parabolic and linear dunes are
drawn around the edge of Lake Frome by Sprigg (1982) (Figure 2.4). There are different types of linear dunes, they may be short or long, irregularly or regularly spaced and they may have Y junctions along their length. (Wasson et al. 1988). Y junctions give an indication of their direction of extension, with the top of the Y opening upwind (Figure 2.4).

There is sand movement at a number of inland sites in the PD. Figures from Sprigg (1982) illustrate the difference in orientation of the relict dunes and the PD extensions at Lake Frome (Figure 2.4) and in the Murray Basin, referred to here as the ‘Mallee’ (Figure 2.5). The Australia-wide pattern of PD dune extensions and sand drifts is shown in Figure 2.3(c). Place names and deserts are marked on the map in Figure 2.6. The direction of PD movement differs from the direction of the relict dunes across southern Australia, except in Tasmania. In the north of Australia, particularly in the Simpson and Great Sandy deserts, there is little difference in the direction suggested by the relict dunes and any present day movement. Much of the movement in these regions is along unvegetated dune crests. The relict dunes in the south of the Great Victoria Desert, Lake Frome region and the Mallee all have a greater eastward component than the present day sand movement. It is these regions of differing dune orientation that are taken by, for example, Bowler et al. (1976) and Sprigg (1982) as an indicator of past and present winds, and that the difference in orientation suggest stronger westerly winds, or more persistent winter-like conditions, at the time the dunes formed. Although the dune orientation is attractive as a simile for the ancient low level winds, the non-linear interactions between wind and dune orientation must be considered.

2.3.1 Age

As outlined above, Australia’s inland dunes can be used as a proxy for past wind regimes. To use them as a proxy for the winds at the LGM it is important to understand when the dunes formed or were last active. Reconstructed ages from the literature will be presented, with locations as numbers on Figure 2.6 and further details in Table 2.2.

There is evidence of dunefields extending off-shore, below the current sea-level, indicating that they formed during the glacial low sea-level stands. These are in north west Australia (1) (Jennings 1975) and South Australia (2) (Sprigg 1979).
|
|---|---|---|---|
|Map | Reference | Details | Age |
|1 | Jennings (1975) | Ocean, NW Australia | Glacial |
|2 | Sprigg (1979) | Ocean, S Australia | Glacial |
|3 | Smith (2002) | L, Murray Basin | 40-10ka |
|4 | Chen et al. (1991) | L, Lake Amadeus | 25-18ka |
|5 | Chen et al. (1995) | L, Lake Lewis | 25-18ka |
|6 | Nanson et al. (1995) | L, Finke | 30-13ka |
|7 | Huntley et al. (1999) | L, Great Victoria Desert | 22ka |
|8 | Duller and Augustinus (1997) | L, NE Tasmania | 30ka-present |

**Table 2.2:** References to dates of dune activity. The Map number refers to the location in Figure 2.6. The details include the ‘dating’ method and the location: ‘Ocean’ means that the dunes are now under the ocean, ‘C’ means radiocarbon dating and ‘L’ means luminescence methods. ka means ‘thousand years ago’
Figure 2.4: Frome relict dune forms, and the present day dune extensions, from Sprigg [1982]
Figure 2.5: Malree relict dune forms, and the overlying present day sand-drifts, from Sprigg (1982)
Figure 2.6: Numbers referring to sites with age estimates, with details in Table 2.2 and in the text. Dune orientations across Australia, re-drawn from Wasson (1986).
Dune features can be difficult to accurately date. Stratigraphic and morphological analysis can tell us qualitatively at what stage aeolian activity occurred, and provides guidelines for the expected bounds on dates. There are a number of ways to date a dune’s activity using the material within the dune, including carbon dating and luminescence techniques. Luminescence dating allows for direct dating of the grains that make up the dunes themselves. It dates the time since the grains were last exposed to sunlight. Aitken (1985) describes the process of thermoluminescence dating. Bioturbation and the wind can move material around in a dune, which creates problems if the dates are being used to create a continuous chronology, but careful attention to the morphological conditions can help in deciding if such mixing might be a concern. Mixing can lead to luminescence ages younger than the date that the sand was first deposited on the dune by large-scale aeolian motion.

Early efforts at dating Australia’s dunes used carbon dating on either organic carbon or ancient soils within the dunes. Bowler and Wasson (1984) used carbon dating on fresh water remains in lunettes at Willandra Lakes, after analysing stratigraphy to determine the layering, and thus ages of deposition, to suggest that lake levels were high from about 50,000 years ago, but the area became arid, with extensive dune building during the last glacial maximum about 20,000 years ago. The scarcity of organic carbon material, and the continuing crystallisation of the carbonates in the soils after the soils have been buried by new aeolian activity, limits the number and usefulness of carbon dates. Some of the results in the literature for luminescence dates on linear dunes are described below.

In the Murray Basin, the synopsis of Smith (2002) indicates dates ranging from 40,000 to 10,000 years ago. The dunes have a high clay content, and their cores are thus very stable, with ages around 125,000 years ago. The dunes are short, with little downwind extension during re-mobilisation, and have no ‘Y junctions’, unlike those in the Simpson desert.

Around Lake Amadeus, the controls on the production of gypsum pellets led Chen et al. (1991) to suggest that there was great seasonality around 54,000 to 44,000 years ago, with periods of high groundwater followed by dry, windy periods. This oscillation may have been on the scale of seasons or over many years. Layers in the dunes around the lake that include quartz from the surrounding regional quartz dunes indicate a dry windy time. The dates from these layers range from 25,000 to 18,000 years ago. Chen et al. (1995) found
similar dates in a quartz layer in the dunes around Lake Lewis (5).

In the region surrounding the Finke river near the town of Finke (6), on the southern edges of the Simpson Desert, there are many linear dunes. Nanson et al. (1995) found dates indicating that the dunes were active between 30,000 and 13,000 years ago. Dates from the base of the dunes are no earlier than 30,000 years ago, indicating a total reworking at that time.

The optically stimulated luminescence ages from the Great Victoria Desert (7), and a preservation of features that might be destroyed by more recent reworking, indicate that there has not been much aeolian transport since 15,000 years ago (Pell et al., 1999). Huntley et al. (1999) took samples from linear dunes in the Great Victoria Desert, and found one LGM age of about 22,000 years ago, and a range of much older ages, indicating that the dunes here have been stable for a long time.

In north east Tasmania, there are dunes in the Ainslie sands, at Waterhouse (8). The dunes are mostly quartz and are oriented west-north-west to east-south-east. Duller and Augustinus (1997) found dates for initial deposition of 44,000 years ago, and re-working at 30,000 years ago. These dunes are still active today, and so aeolian deposition after 30,000 years ago may have been re-worked, and thus evidence of LGM activity may have been lost.

There is obviously a need for further dating across the continent, particularly in the west. From the results given here, and the results of dry LGM conditions, it is likely that there was a strong capacity for dune building during the LGM. There are also other periods that show up amongst the dates. There was some activity during the Holocene, some much older activity and some dunes that are still active today.

2.4 Synopsis

2.4.1 Temperature and moisture availability

Conditions much cooler than the present day are indicated at Lake Eyre and in the alpine regions in the south east of the mainland and Tasmania. Cool LGM temperatures have been inferred from high lake levels in south eastern Australia. Pollen sequences from the north east of Queensland, south eastern Australia and south west Western Australia have been interpreted as showing evidence of cooler temperatures at the LGM. Although the limitations on reconstructing
temperatures from proxy evidence must be recognised, the overall picture is of a cooler environment in Australia at the LGM. There are only a few sites with evidence of the magnitude of this cooling.

The evidence presented in this section can be interpreted as showing a more continental environment, with fewer southward monsoonal incursions. Dry lake beds and active dune building indicate dry conditions across central Australia. At the edges of the arid zone, where there are permanent lakes today, there is a record of those lakes persisting through the LGM, along with some lakes that are now dry, perhaps indicating lower evaporation. On the southern edges of the continent there is evidence of drier conditions, although periglacial features in Tasmania are interpreted as a decrease in temperature at the LGM, with no change in precipitation.

The evidence above indicates a generally drier and cooler environment, with local variations. In the following chapters the factors influencing the changes in moisture availability and temperature will be investigated.

### 2.4.2 Paleo-circulation

The ages gained from direct dates and from association of the conditions in one area with those nearby, led to a relatively clear signal that dunes were more active at the LGM. There are many instances of dunes forming on dry lakes and generally increased dune activity at the LGM. As the climate became drier at the LGM, and lake levels in arid regions receded, the conditions would have been right for extensive lunette building.

Although the whorl of linear dunes in Australia’s interior may appeal as a direct proxy for the circulation at the LGM, there are many controls on an individual dune’s orientation that may lead to its final orientation differing from the low level winds at the time of formation. Some of these controls will be explored further in Chapter 8. Ultimately, accounting for the controls on the orientation of relict dunes will give a good appreciation of the wind in which they formed, and possibly the seasonality of that wind.
2. Proxy evidence of the Australian climate at the LGM
Chapter 3

Model description, boundary conditions and mean climatology

3.1 Introduction

Only longer term (monthly) averages are available from the models involved in the Paleoclimate Modelling Intercomparison Project (PMIP). For much of the analysis in this thesis, less common fields and more frequent data are required. For these data, the output from the Melbourne University model is used. In this chapter the model will be described, along with the boundary conditions prescribed for both the Present Day (PD) and LGM simulations. A comparison is made with data to assess how well the model portrays the current climate, and thus its adequacy to answer the questions outlined in this thesis.

3.2 Melbourne University General Circulation Model

The Melbourne University General Circulation Model (MUGCM) is an atmospheric general circulation model (GCM), and has been used to simulate the present and LGM climate and run the experiments described later in this thesis. A guide to the model code, use and analysis of output is available in Hope (2000). The model was originally based on the hemispheric model described in Bourke et al. (1977) and McAvaney et al. (1978). The prognostic variables of vorticity, divergence, temperature, moisture and surface pressure are expressed as spherical harmonic series. In the version used here these are rhomboidally
The non-linear physics are calculated on a Gaussian grid, which are the zeroes of the appropriate order Legendre polynomial. The longitude spacing is 5.6°, while the latitude spacing is Gaussian, with an average spacing of 3.4°. There are nine terrain following sigma levels in the vertical. The fraction of the surface pressure at each level (sigma) is 0.991 closest to the ground, 0.926, 0.811, 0.664, 0.500, 0.336, 0.189, 0.074 and 0.009. These levels include lower levels of the stratosphere but it is not well resolved. The lowest level is on average at 75 m above the surface. Noone and Simmonds (2002) provide a brief overview of some of the developments and parameterisations in the MUGCM. There are differences in the moisture transport in the MUGCM version that Noone and Simmonds (2002) describe and that used here, the version used by Noone and Simmonds (2002) has semi-Lagrangian moisture transport, while the version used here uses spectral transport for the moisture field. Some of the physics and parameterisation schemes are described briefly below.

The incoming solar radiation (insolation) at the top of the atmosphere is calculated from the date prescribed at run time. The model uses equations from Berger (1978) to calculate the orbital parameters from the date and provides the changes in the seasonal timing of the insolation. There is a full seasonal and diurnal cycle. The atmospheric radiation calculations follow Fels and Schwarzkopf (1975) and Schwarzkopf and Fels (1991), as documented for the MUGCM in Weymouth (1987). The radiation scheme interacts with the fractional clouds calculated from the moisture and temperature for three layers, incorporating two sigma levels each, not including the lowest and top two levels, (Argete, 1993). At the surface a radiation balance is performed over land and sea-ice, but the sea surface temperatures (SSTs) and snow are prescribed. The sea-ice temperature and albedo calculations account for leads.

The moist convection follows Manabe et al. (1965), with dry convective adjustment as in Weymouth (1987). The precipitation in the R21 resolution is enhanced over high topography, but, tests with a higher resolution version (R31) show that increasing the resolution leads to further problems with the precipitation. This is because, as the resolution increases, the Gibbs ripples in the topography increase, causing further irregularities in the precipitation field. Lindberg and Broccoli (1996) suggest a new smoothing method to apply to such spectral ripples in the topography to allow a more realistic response in the precipitation. Using the R21 resolution this ‘fix’ is not so important, although
there is still unrealistically high precipitation over high topography.

The majority of paleo proxy evidence is from surface variables, and thus the surface layer formulation is of importance. The details are described in Simmonds (1985). The Monin-Obukhov similarity theory provides the equations to define the vertical profiles of the wind, potential temperature and moisture, which are solved using the analytic curves of Louis (1979). The roughness length is prescribed as 29.62 cm over land, which gives a momentum drag coefficient of 0.004 for neutral conditions. In the new module that calculates the 10 m wind for the calculation of the potential of the wind to shift sand, the roughness length is re-set to a value specific to a sandy surface in windy conditions. Over ocean the roughness length is calculated from the friction velocity.

The 2 m temperatures are calculated in this version of the model for ease of comparison with NCEP2 and other models. The method used is that of Hess et al. (1995), described below for calculating the magnitude of the 10 m winds.

The soil moisture scheme is a two layer bucket model, with the top layer designed to respond to diurnal variations and the lower layer to respond more slowly. The scheme is from Deardorff (1977), modified following Hunt (1985). Evaporation is particularly sensitive to the surface water, to a depth of 0.5 cm, but the longer term storage in the deeper soil moisture layer also has implications for the long-term evaporation values. When the depth of the lower layer is deeper, the mean evaporation increases. A number of depths of the deep soil layer were tested for their influence on evaporation. With a soil depth of 2.0 m, the MUGCM evaporation for Australia, compared with mean monthly evaporation data synthesised by the Australian Bureau of Meteorology (Chiew et al., 2002), was too high year round. With a shallower bucket of 50 cm the evaporation was too high in winter, but too low in summer. This result indicates some variability with season in how the model responds to soil moisture, but for the subsequent simulations the 50 cm depth was chosen.

The snow albedo is dependent on temperature, with temperatures cooler than -1.0°C having the greatest reflection, and then a gradient of reflection to temperatures above 1.0°C. The ocean albedo is calculated as a function of the sun’s zenith angle, following Payne (1972), with no dependence on wind speed and prescribed dependence on cloud cover. The albedo of the land (\(\alpha\)) is determined from the soil moisture content, with very wet regions having the albedo of dense vegetation, and very dry that of sand, from Laval and Picon.
The formula for the moisture dependent scheme is:

\[
\alpha = \begin{cases} 
-\frac{w}{w_{max}} + 0.4, & \text{if } \frac{w}{w_{max}} \leq 0.2 \\
-0.15\frac{w}{w_{max}} + 0.23, & \text{if } \frac{w}{w_{max}} \geq 0.2 
\end{cases}
\]  

(3.1)

where \( w \) is the soil moisture, and \( w_{max} \) is the maximum value of soil moisture.

The PD control simulation was run for 21 years, and all other simulations run for at least 11 years. The first year of each run was discarded to allow the model physics to respond to the prescribed boundary conditions, and produce an appropriate climate, independent of the initial state, which for the response of momentum to thermal changes can take on the order of tens to hundreds of days (Simmonds, 1985).

Each year is like a member of an ensemble as the prescribed SSTs do not vary from year to year. Thus a comparison between the control and experiment, based on the Student t-test (Chervin and Schneider, 1976), will not test the inter-annual variability as with varying SSTs, but will give an indication of the noise within the model, just as if there were 10 or 20 ensemble members. The stippling on all subsequent anomaly figures reflects a difference significant at the 99% level calculated following the method outlined in Chervin and Schneider (1976).

In order to carry out the experiments in this thesis a number of new parameterisations were added to the MUGCM. Most will be outlined in the section describing the method for the experiment in the relevant Chapter. The calculation of the 10 m wind, used in the development of a value for the sand shifting potential, is described below.

### 3.3 10 m wind calculation

The lowest wind data available in the model output is at the lowest sigma level, 0.991. This level is at a height of approximately 75 metres in the subtropics. A standard reference height, and the usual anemometer height, is 10 m, and this is also the height of wind data for which the equations of sand shifting potential and orientation discussed in Chapter 8 have been developed. Calculating the magnitude of 10 m winds is a reasonably standard step in GCMs, but usually the turning from the lowest sigma level to 10 m is not described. For the purpose here any Ekman turning is very important to the resultant wind direction, so...
it is included in this calculation of the 10 m winds.

### 3.3.1 Magnitude of winds at 10 metres

The predictor-corrector iterative method of [Hess et al. (1995)] is recommended for use in models taking part in the AMIP for estimating the magnitude of the 10 m winds, as described at [AMIP (1998)] . The program that does this is also available from the web-site. The method is best applied to GCMs, such as the MUGCM, that utilise the curves of [Louis (1979)] to determine their surface fluxes.

The method uses the bulk Richardson number \( (Ri_b) \) to solve the profile relationships for \( U \), the mean wind, \( \Delta \Theta \), the change in potential temperature between the surface and the anemometer height and \( \Delta Q \), the change in specific humidity. The process begins by estimating the scaling parameters, \( u_* \), \( \Theta_* \) and \( Q_* \) in equations 11 to 13 of [Hess et al. (1995)] , using the values of \( U \), \( \Theta \), and \( Q \) at the lowest sigma level. Surface values are denoted with the subscript 0 (e.g. \( \Theta_0 \)), while unscripted values are at the lowest sigma level or at the anemometer height, depending on the context. The equation to estimate \( u_* \) (Equation 11 in [Hess et al. (1995)]) is:

\[
\frac{kU}{u_*} = \frac{\ln (z/z_0)}{F_M (Ri_b, z/z_0)} \quad (3.2)
\]

where \( k \) is the von Karman constant, \( F_M \) is the exchange coefficient for momentum used by [Hess et al. (1995)] which is from [Holtslag and Beljaars (1989)], \( z \) is either the height of the lowest sigma level or the anemometer, depending on the step, and \( z_0 \) is the roughness length. A roughness length of 1 cm is used here because the 10 m wind is being calculated for use with equations of sand motion, and 1 cm is an appropriate roughness length for rippled sand, [Bagnold (1941)] .

The exchange coefficient \( (F_M) \) is determined using the the bulk Richardson number, \( Ri_b \), which is initially estimated for the full layer between the surface and the lowest sigma level using the equation:

\[
Ri_b = \frac{g \Delta z}{\Theta_v} \frac{\Delta \Theta_v}{|\Delta U|^2} \quad (3.3)
\]

where \( g \) is gravity, and \( \Theta_v \) is the virtual potential temperature. The calculation of the exchange coefficient is dependent on the stability. In the stable case \( (Ri_b \)}
3. Model description, boundary conditions and mean climatology

> 0) Hess et al. (1995) parameterised this as:

\[
F_M = \frac{1}{1 + 10R_i b(1 + 8R_i b)}
\] (3.4)

while in the unstable case \((R_i b < 0)\), the equation of Louis (1979) is used:

\[
F_M = 1 - \frac{10R_i b}{1 + 75\left(\frac{k^2}{z_0}\right)^2 \sqrt{-R_i b \frac{z}{z_0}}}
\] (3.5)

Using the estimates from Hess et al. (1995) of the scaling parameters, \(u_*\) etc., the Obukhov length, \(L\), is calculated.

\[
L = \frac{u_*^2}{gk} \left[ \Theta_s(1 + 0.61Q_0) + 0.61\Theta_sQ_s \right]
\] (3.6)

With a value for \(L\), the Dyer-Businger profile functions shown in Hess et al. (1995) can be used to predict the value of U at 10 m. For momentum:

\[
\frac{kU}{u_*} = ln\left(\frac{z}{z_0}\right) - \Psi_M\left(\frac{z}{L}\right) + \Psi_M\left(\frac{z_0}{L}\right)
\] (3.7)

where, in unstable conditions,

\[
\Psi_M\left(\frac{z}{L}\right) = 2ln(1 + x) + ln(1 + x^2) - 2 tan^{-1}x
\]

where \(x = (1 - 16\frac{z}{L})^{\frac{1}{4}}\), and in stable conditions:

\[
\Psi_M\left(\frac{z}{L}\right) = -5\frac{z}{L}
\]

The value of \(R_i b\) can then be calculated at the anemometer height, 10 m. With the estimated value of \(R_i b\) at 10 m, U in Equation 3.2 is again calculated: the ‘corrector’ step. The last two steps can be repeated until the iterations differ by less than 5%, which for the wind is usually very few iterations.

The calculations above give the magnitude of the 10 metre winds. The calculation of the direction of the 10 metre winds is described below.

3.3.2 Turning from the lowest sigma level to 10 metres

In the computer program provided to AMIP participants the magnitude is broken into the vector components by using the directions of the wind at the first
sigma level. Given that this level is generally at 75 m in the MUGCM and the surface layer can vary from about 10 to 100 m, there may well be Ekman turning between the lowest sigma level and 10 m. This turning is due to the increasing influence of surface friction closer to the ground. This causes the wind to be directed toward lower pressure, to the right of the geostrophic wind in the Southern Hemisphere. During the day, convective activity leads to a deep well mixed boundary layer, with little change in wind direction through the first 100 m, often less than 10°. At night the planetary boundary layer is shallow, and turning can be in excess of 30°. To calculate the directions of dunes from the winds, or how much the mean wind differs from the sand shifting potential directions, an accurate representation of the wind’s direction is required.

Hess et al. (1995) suggest using the method outlined in Holtslag and van Westrhenen (1989) to calculate the degree of turning between the directions from the lowest sigma level to 10 m. In the appendix of Holtslag and van Westrhenen (1989) they suggest an equation fitted to an empirical curve of the mean variation of the wind direction with height for different classes of Obukhov length under stable conditions. They found that the maximum rotation would be 45° in stable conditions, in good agreement with the classical Ekman spiral. Nieuwstadt (1983) used a model to solve the Ekman-layer equations and found a maximum turning of 20° rotation through the depth of the boundary layer in very unstable conditions. Holtslag and van Westrhenen (1989) describes the empirical curve for $D_z$, the degree of turning between the surface and the height $z$, with the equation:

$$\frac{D_z}{D_h} = d_1(1 - e^{-\frac{h}{L}}), \text{ where } d_1 = 1.23 \text{ and } d_2 = 1.75.$$  \hspace{1cm} (3.8)

$D_h$ is dependent on the stability, tested here by the height of the atmospheric boundary layer, $h$, divided by the Obukhov length, $L$. For very unstable conditions ($h/L \leq -10$), $D_h$ is set to 20°, for $-10 < h/L < 0$, $D_h$ takes the value:

$$D_h = 20 + 25(1 + \frac{h/L}{10})$$  \hspace{1cm} (3.9)

and for stable conditions, $h/L \geq 0$, $D_h=45°$.

The direction of the wind vectors is known at the lowest sigma level, so the degree of turning between the surface and the lowest sigma level is first calculated, giving the direction of the vectors at the surface. Equation 3.8 is then used to calculate the turning to 10 m from the surface, and the actual
vector orientations obtained by adding the turning to the surface directions.

The stability test and Equation 3.8 require the calculation of the height of the planetary boundary layer, $h$, and the Obukhov length, $L$. The Obukhov length used in the calculation of the magnitude of the 10 m winds is used. The height of the planetary boundary layer is calculated using the iterative formulation given in Kiehl et al. (1996), which determines where the Richardson number falls below the critical value of 0.3, adjusting for convective overturning, Holtslag and Boville (1993).

3.4 Boundary conditions for the Present Day simulation

Insolation

The PD incoming solar radiation at each latitude, and its seasonal variability is calculated within the MUGCM from the date input at the start of a run. From this date the eccentricity, obliquity and date of perihelion are calculated, using the equations of Berger (1978).

The date of perihelion is the date when the earth passes closest to the sun on its elliptical orbit, and this date moves through a calendar year in a cycle varying from 19 to 23 thousand years. At present it is January 3rd, thus there is slightly more insolation in summer in the Southern Hemisphere, and slightly less in summer in the Northern Hemisphere.

The eccentricity refers to how circular the Earth’s orbit around the sun is. This ranges from 0.0 (circular), to 0.07 (elliptical), with a period of about 95 thousand years. The more elliptical the path is, the more important the date of perihelion is to the seasonality of insolation. At present it is nearly circular with an eccentricity of 0.017, and the Southern Hemisphere receives 6.7% more insolation in summer than the Northern Hemisphere. When the Earth’s orbit is at its most elliptical the difference in insolation is approximately 28%.

The obliquity refers to how far the Earth’s axis deviates from the vertical (perpendicular to the ecliptic - the plane that the orbit of the earth is on). The range is from approximately 22° to 24.5°. At present it is 23.5°. It was 24.5° approximately 9000 years ago. This change has a period of 41 thousand years. The larger this angle the further pole-ward the tropics of Cancer and Capricorn are, and the more pronounced the subtropical seasons are.
3.4 Boundary conditions for the Present Day simulation

Radiative gases

The carbon dioxide concentration is set to a value appropriate to the choice of sea surface temperatures. Generally the accepted values are 345 ppmv for the PD and a ‘pre-industrial’ level of 280 ppmv. The value chosen for the control simulation is 330 ppmv. The vertical ozone profile is also prescribed seasonally for each latitude.

Topography

The topography is from $1^\circ \times 1^\circ$ data from Gates and Nelson (1975), extrapolated to the model resolution. The model resolution is reasonably large, and much of the sub-grid scale orography is smoothed out. To combat this problem and present a better representation of the surface to interact with the dynamics, the variability of the $1^\circ \times 1^\circ$ data within the model grid box is calculated and one standard deviation added to the topography as an ‘envelope’. Sigma level output that is transformed to pressure levels is adjusted to account for the envelope (Walsh, 1994; Walsh et al., 2000).

Sea Surface Temperatures

It cannot be assumed that there will be the same interannual variability of sea surface temperatures (SSTs) at the LGM as at present. Thus an average of modern temperatures should be used as the SST control and that from which the LGM anomalies are taken. Determining the years that this average should encompass is not trivial, as there is strong interannual variability in the oceans (particularly linked to ENSO), the years after the mid 1990s are anomalously warm, while before 1979 there was no satellite data, and thus there were limited data values across the oceans. The poor observational coverage prior to 1979 is why the SSTs are not set to 1950 as the external factors such as the solar variables are. Given these constraints, the period specified as the best control by the paleoclimate modelling intercomparison project (PMIP), (Joussaume and Taylor, 1995), is the average of values from 1979 to 1988. The SSTs used in the MUGCM control run are the average of Reynolds (1988) SSTs from 1982 to 1987. This includes half of the years recommended for a PMIP control simulation, however, it is a period including a number of strong El Niño events, which will lead to anomalously warm SSTs in the eastern tropical Pacific Ocean compared to the PMIP control period of 1979-1988; see Figure 3.1. This ‘El
Niño-like’ mean SST pattern will likely produce a climate more similar to El Niño than the other PMIP models, with potentially warmer and drier conditions across Australia. If this is the case, it would alter the LGM anomaly, producing cooler and wetter conditions across Australia compared to models forced with the full 1979-88 SSTs.

Figure 3.1: Annual 1982-87 Reynolds sea surface temperatures minus 1979-88 annual GISST2.3. The increment is 0.2 degrees, negative anomalies are dashed

Sea-ice

The sea-ice extent, concentration and thickness is prescribed. The data is interpolated from mid monthly values from the DMSP SSM/I data set from the National Snow and Ice Data Center, Colorado, USA. The sea-ice temperature is arrived at via a radiative balance \cite{Budd1991}. For grid-boxes with some fraction of ocean amongst the ice, the ocean temperature is set to -1.8°C.

3.5 Present Day simulation results and comparison with data

3.5.1 Data

An assessment of the present day climate requires some comparison with actual measurements. The Australian and global data and reanalyses used here and elsewhere in this thesis are outlined below.

Australian precipitation data are from a high quality monthly dataset, \cite{Jones1997}, where station data has been quality controlled and interpolated to a 0.25° × 0.25° grid for the last century. High quality grids of
Australian maximum and minimum temperature data have also been produced in the same way by the National Climate Centre at the Australian Bureau of Meteorology, following Torok and Nicholls (1996).

Estimated evaporation for Australia on grids at 0.1°x0.1° resolution have been made available by the Australian Bureau of Meteorology (Chiew et al., 2002). These include estimates of the actual and potential evaporation, and includes data from a range of sources including temperature and wind data, some ground-truthing and satellite data. These are climatological mean monthly averages.

Global precipitation data is from the Xie and Arkin merged monthly precipitation estimates, Xie and Arkin (1996, 1997). This dataset is calculated from a combination of gauge data, satellite estimates and model output. It was obtained from the Climate Analysis Center at the U.S.A. National Ocean and Atmospheric Administration.

Other global data is from the NCEP-DOE AMIP-II Reanalysis (NCEP2), Kanamitsu et al. (2002). This is a four dimensional assimilation of data into the NCEP GCM, with a spectral resolution triangularly truncated at 63 waves and 17 vertical levels. The reanalyses are available on a 2.5° x 2.5° global grid at 6 hourly intervals from 1979-2000.

There is a range of quality associated with different fields from the NCEP2 reanalyses. Fields such as temperature and pressure are directly assimilated into the reanalyses and are deemed of high quality. Other fields, particularly the hydrological fields including precipitation, evaporation and soil moisture, are the result of the parameterisations in the assimilation model itself, and ranked as lower quality (Kanamitsu et al., 2002). The observed precipitation trends in the south west of Western Australia, which showed a sharp decline in the 1970s, provide a good test of the ability of the reanalyses to capture appropriate variability and trends. A brief examination of the winter precipitation totals in the south west of Western Australia shows that the reanalyses capture the observed year to year variability, but not the trend.

3.5.2 MUGCM Present Day mean results

Simmonds et al. (1988) show global maps and cross sections of many of the mean January and July fields, and comparisons with data, from an earlier version of the MUGCM. The results from the control simulation used for this thesis are
Figure 3.2 and Figure 3.3 show the mean DJF and JJA mean sea-level pressure (PMSL) from the MUGCM and NCEP2 and their difference. In DJF the major features are similar though the Aleutian low in the MUGCM simulation is displaced eastward. Through Australia and southeast Asia the pressure is lower in the MUGCM. Around Antarctica the circumpolar trough is less well defined in the MUGCM. The MUGCM simulation of PMSL for JJA also has similar major features to NCEP2, again with less well defined features around Antarctica. Australia has lower pressures in the MUGCM than NCEP2, with the subtropical ridge less well defined in Australia and the Indian Ocean. In both seasons the differences over Antarctica are large. The high topography over Antarctica means that the creation of the pressure values at sea-level requires a transfer process. Any variation in the topography and transfer scheme will compound any real differences between MUGCM and NCEP2.

To better assess the transport directions and strength in the lower atmosphere the mean wind vectors from MUGCM and NCEP2 at 850 hPa, along with their differences, are shown in Figures 3.4 and 3.5. The NCEP2 data is extrapolated to the MUGCM resolution for ease of comparison, and then both are ‘thinned’ so that only every second vector is plotted. Many of the features are consistent with the pressure fields. For example, in DJF the gyres in the Pacific are more zonally extended in the MUGCM. The zonal extension of the Pacific gyres leads to consistent easterly flow right across the Pacific to the south of the Equator. The flow in the Pacific and north Atlantic is more zonal than in NCEP2. The band of westerlies in the Southern Hemisphere does not extend as far south in the MUGCM as the NCEP2, particularly south of the Indian Ocean in winter, where the easterlies on the Antarctic coast are stronger in the MUGCM. In Africa, the mean wind across the north of the continent is stronger in the MUGCM. Over the Australian continent the size and orientation of the vectors is similar between NCEP2 and the MUGCM. The oceanic gyres in JJA are more similar than in DJF. The weaker subtropical ridge over Australia is expressed as an eastward shift in the centre of the mean wind vectors, although the latitudinal ranges are very similar. The stronger trades in the MUGCM extend right across the north of Australia, and the westerlies are also stronger in the Australian region.

The difference of the mean MUGCM temperature 2 m above the surface from the NCEP2 for the years 1979-2000 is minimal over the oceans, see Figures 3.6
3.5 Present Day simulation results and comparison with data

Figure 3.2: DJF mean sea-level pressure. (a) MUGCM, (b) NCEP2, contour interval 5 hPa and (c) MUGCM - NCEP2, contour interval 4 hPa.
Figure 3.3: JJA mean sea-level pressure. (a) MUGCM, (b) NCEP2, (c) MUGCM - NCEP2. Contour interval 5hPa
3.5 Present Day simulation results and comparison with data

Figure 3.4: DJF Wind vector at 850 hPa height. (a) MUGCM, (b) NCEP2 (c) MUGCM - NCEP2, interpolated to R21 resolution, the reference vector length is drawn below each map in ms$^{-1}$
Figure 3.5: JJA Wind vector at 850 hPa height. (a) MUGCM, (b) NCEP2, (c) MUGCM - NCEP2, interpolated to R21 resolution, the reference vector length is drawn below each map in ms$^{-1}$. 
and 3.7 as would be expected given that the MUGCM is forced with prescribed SSTs. The pattern of mean seasonal global temperatures is similar, but the coarse spectral topography in MUGCM leads to the temperature contours over topography being broader, particularly in the Americas. Over Australia the temperature pattern is similar. In both summer and winter most of southern Asia, Africa and South America are cooler in the MUGCM than NCEP2. In JJA the north of the Northern Hemisphere continents are warmer in MUGCM, as is Antarctica in DJF. This suggests that MUGCM is too warm at high latitudes in summer. Over Australia the differences between the MUGCM and NCEP2 are slight. Figures 3.6 and 3.7 show only one contour line over the continent, showing differences generally less than 2 K, and no more than 6 K. The seasonality is slightly depressed, with cooler temperatures in summer and warmer in winter. Given that each average is over different years these differences in magnitude would be expected. Thus, the MUGCM captures the expected global seasonal patterns in temperature, and there are only minor errors in the magnitude and seasonal variation.

The global precipitation signal in the MUGCM is compared to that from Xie and Arkin (1996, 1997). The MUGCM does not simulate the Pacific intertropical and south Pacific convergence zones in DJF (Figure 3.8) perfectly, but many of the features around the continents, such as the dry region to their west are well simulated. Like the intertropical convergence zone, the south Pacific convergence zone is a region of persistent convection and cloudiness, but located in the south west Pacific, sloping from the north west to the south east. Over Australia the general structure of the DJF rainfall in MUGCM is good. Over the southwest MUGCM simulates drier conditions than Xie and Arkin. The precipitation totals over the high mountains on the land to the north of Australia are unrealistically high in the MUGCM. This is a problem common to most spectral models. In JJA (Figure 3.9) the MUGCM intertropical convergence zone is captured but the topographic effect is still evident.

Over Australia the differences between the Australian high quality gridded rainfall dataset and the MUGCM output are shown in Figure 3.10. The datasets are quite disparate in their resolution, so they were both interpolated to an intermediate scale of 1° × 1°. There are large wet biases in the precipitation signal in eastern Australia, particularly in summer. Central and western Australia are represented well in summer. In winter the MUGCM has a slight wet bias over most of the continent but the precipitation pattern is represented rea-
The percentage differences show some large errors - particularly in the north east in summer. However, the differences are also not atypical of the comparative differences shown by models involved in the Atmospheric Modelling Intercomparison Project (AMIP) (Zhang et al., 2003).

3.6 LGM boundary conditions

The LGM experiments are run for at least eleven years, with the first year discarded. This is as if there were ten ensemble members as discussed at the end of Section 3.2. The boundary conditions used to simulate the LGM are from the paleoclimate modelling intercomparison project, PMIP. Many of the boundary conditions are from [CLIMAP] (1981). For the [CLIMAP] (1981) maps, the LGM is set to 18,000$^{14}$C or 21,000 years ago [CLIMAP] (1976).

Crosta et al. (1998) use a different method to test the fauna from cores used in the production of the CLIMAP maps, as well as some extra cores. They find that the extent in winter is similar to CLIMAP, except north of the Weddell Sea (Atlantic sector), where there is more sea-ice, and in the eastern Pacific sector where there is less. They concluded that the sea-ice extent in summer is less than that in CLIMAP. However, for consistency with other PMIP results, the sea-ice extent is set as that outlined by [CLIMAP] (1981).

Since [CLIMAP] (1976), proxy measures of the LGM climate of the oceans, atmosphere and cyrosphere have continued to be collected, and the methods of climate reconstruction have continued to be developed. Unfortunately there has been a divergence in the methods of reconstructing the climate, particularly the SSTs, from the data between international groups (Barrows, pers. comm. 2000), and an updated global gridded map of boundary conditions for input to GCMs, such as [CLIMAP] (1981) has not been created. However, a new protocol for a synthesis of new and revised analysis of LGM proxy evidence has begun with a meeting in 1999, termed EPILOG (Environmental Processes of the Ice age: Land, Oceans, Glaciers) (Mix et al., 2001). This will be an exciting new dataset to use when it becomes available, however at this stage the best estimate for input to GCMs is from [CLIMAP] (1981). Using [CLIMAP] (1981) maps will also allow for comparison of the MUGCM results with the model results from the PMIP.
Figure 3.6: DJF temperature at 2m height. (a) MUGCM, (b) NCEP2, Contour interval 5 K (c) MUGCM - NCEP2. Contour interval 4 K, the lowest contour level is +/- 2 K. Negative contours are dashed.
Figure 3.7: JJA temperature at 2m height. (a) MUGCM, (b) NCEP2, Contour interval 5 K (c) MUGCM - NCEP2. Contour interval 4 K, the lowest contour level is +/- 2 K. Negative contours are dashed.
Figure 3.8: DJF precipitation. (a) MUGCM, (b) Xie and Arkin (1996, 1997). Contours at 0, 0.5, 1, 2, 5, 8, 10, 13, 16, 20, and 40 mm day$^{-1}$
3. Model description, boundary conditions and mean climatology

Figure 3.9: JJA precipitation. (a) MUGCM, (b) Xie and Arkin [1996, 1997]. Contours at 0, 0.5, 1, 2, 5, 8, 10, 13, 16, 20, and 40 mm day$^{-1}$.
Figure 3.10: Mean MUGCM precipitation minus high quality gridded Australian precipitation, 1960-90. Both are interpolated to 1° x 1° grid. (a) DJF, (b) JJA, contours are variable: -250, -200, -150, -100, -50, -25, -10, 0, 10, 25, 50, 100, 150, 200 mm month$^{-1}$. Negative contours are dashed and the zero contour is bold.
3. Model description, boundary conditions and mean climatology

Insolation

The insolation at 21,000 years ago was not all that different from today. The date of perihelion was January 15, meaning that the insolation was slightly greater in the southern summer. This is close to the present date of January 3. The eccentricity of the orbit was near circular at 0.019, close to the present day value of 0.017. The obliquity of the Earth’s axis, and hence the latitude of the tropics of Cancer and Capricorn was at 23\(^\circ\), meaning the area of between the tropics was slightly less than today.

Given the similarity between the orbital parameters at the LGM and today, modifying the insolation alone would not capture all the memory from the previous climatic regime. The LGM was the culmination of a period of about 80,000 years of cooling. Such small changes in insolation between the present day and the LGM might have some effect on the temperature of the large continental masses, but little effect on other systems. Examples of the memory in the Earth system include the thermohaline circulation of the ocean that may take millennia for waters affected by surface conditions to again re-surface, ice sheets that take thousands of years to build and even sea-level can be affected by the gradual rebound of the coasts which massive ice sheets once weighed down. Thus some of these boundary conditions will also be prescribed.

Topography and land extent

A major change evident at the culmination of 80,000 years of cooling was the extended Northern Hemisphere glaciers. These are prescribed following Peltier (1994). The height of the new glaciers is included in the LGM topography. The topography is also increased to account for the 120 m drop in sea-level at the LGM. Figure 3.11 shows the topography for the PD, LGM and the increases at the LGM. The drop in sea-level exposes land. Of particular relevance is the land exposed to form a land bridge to the north of Australia and between the mainland and Tasmania to its south. Lake Carpentaria, on the exposed land to the north (Yokoyama et al., 2001b) is not included in the land-sea mask.

Radiative gases

The carbon dioxide in the atmosphere is estimated from fossil air in ice-cores from Greenland and Antarctica, for example, as found by Petit et al. (1999) and is set to 200 ppmv.
3.6 LGM boundary conditions

Sea Surface Temperatures

The SSTs were prescribed from the August and February reconstructions of CLIMAP ([CLIMAP 1981](#)). The values for the other months were determined by interpolating between the August and February values following the seasonal cycle from the control simulation. The SST reconstructions from CLIMAP ([1981](#)) will be referred to simply as CLIMAP or LGM SSTs. The MUGCM PD and LGM SSTs and their differences are shown for February in Figure 3.12 and August in Figure 3.13. Surprisingly there are regions in the Pacific and Indian Oceans where the temperature is reconstructed as being slightly warmer than the present day. One region that stands out against the surrounding anomalies is a ‘hot spot’ off the east coast of Australia. This region was defined by one marine core and this was re-assessed by [Anderson et al. 1989](#) and [Trend-Staid and Prell 2002](#) who found that it was not as warm at the LGM as suggested by the CLIMAP ([1981](#)) reconstruction. The results of [Barrows and Juggins 2005](#) confirm this finding. The ocean temperatures around Australia are also in a region stated in CLIMAP ([1976](#)) to be of lower quality than the data in the North Atlantic.

Sea-ice

The sea-ice extent is also from CLIMAP ([1981](#)), and the seasonal cycle is calculated in much the same way. The seasonal cycle of the extent of Antarctic sea-ice in the CLIMAP ([1981](#)) LGM reconstruction is not all that large, with almost as much sea-ice in summer as winter. Figure 3.14 shows both the LGM and PD extent of sea-ice in the MUGCM boundary conditions for February and August.

The LGM sea-ice extends far beyond the PD sea-ice. In the Southern Hemisphere the LGM sea-ice concentration is calculated as a gradient from the mid-point of the PD sea-ice extent to the LGM ice edge. The half-way point between the PD mid-point of sea-ice extent and the LGM ice edge is set to a concentration of 85%, and a linear gradient from a concentration of 95% at the PD mid-point to 85% is calculated for the points in between. The sea-ice concentration is set to 5% at the edge of the ice extent, and a linear gradient is calculated from 85% at the half-way point to 5% at the edge. A similar method is used in the Northern Hemisphere, but land-points between the mid-point of the PD extent and the LGM extent are not included in the gradient. The sea-ice extent
for February and August is set by CLIMAP, and the extent in the intermediate months is estimated as a sinusoidal curve between the two. The concentration is calculated to each month’s LGM extent.

To simulate appropriate temperatures over the new extensive sea-ice in summer, modifications to the calculation of the radiative balance over sea-ice were needed. Allowing the heat balance of in and out-going fluxes at the sea-ice surface to evolve freely resulted in warming over the ice in the summer long term mean. Although some warm values might be expected on a short term basis the long term values simulated were of a magnitude that, if the ice were allowed to respond to the atmospheric forcing, it would not last the summer. The reason for the warm atmosphere may be that the prescribed sea surface temperatures are not consistent with the extent of sea-ice or from an inaccuracy in the radiation balance in the MUGCM. Meehl et al. (1998) suggests that the moist physics used in their model produces too much moisture in the clouds at high latitudes, resulting in over-enhanced long-wave feedback. The MUGCM may also suffer from this problem, but that will not be explored here. As for the PD simulation, the LGM SSTs amongst the ice are set to -1.8°C. Since the SSTs are constantly resetting the radiative balance at the ocean surface it was believed that a similar forcing would help to maintain the temperatures expected in the long term mean over sea-ice. The surface temperature of the ice was never allowed to become warmer than 0°C. The result of forcing the ice to remain cooler than 0°C produced a smoother transition in temperature from sea-ice to ocean which will not affect the baroclinicity to such an extent as the original simulation. In Australia the response to this change was minimal.

3.7 Climate regions

The climates of Australia can be categorised in a number of ways including regions with similar rainfall-temperature regimes, regions that are influenced by the same air-masses or where the vegetation is similar (Linacre and Hobbs 1977). The climatic regions chosen for averaging temperature and precipitation are based broadly on those defined with the Köppen system, shown in the maps in Gentilli (1972), and Stern et al. (1999). Figure 3.15 shows the regions defined for climatological averages. For some analysis the southern south east region (SE2) and the eastern region (SE1) are combined. The north is dominated by the summer monsoon, the central region is usually under the subtropical
Figure 3.11: Topography used in the MUGCM simulations for (a) PD, (b) LGM and (c) LGM-PD. The contour interval is variable, for (a) and (b) it is at 200, 1000, 2000 and 4000 m, while for the difference it is at 120, 1000 and 2000 m.
Figure 3.12: February SST, (a) PD and (b) LGM, contour interval 4°C; and (c) difference, contour interval 1°C. Negative contours are dashed, zero line bold.
Figure 3.13: August SST (a) PD and (b) LGM, contour interval 4°C; and (c) difference, contour interval 1°C. Negative contours are dashed, zero line bold.
Figure 3.14: Sea-ice extent prescribed in the MUGCM, for (a) February and (b) August. The PD extent is shown in darker grey, while the LGM is both dark and light grey.
ridge and is dry while the eastern region (SE1) receives rainfall from the east as well as the west, and the south west and southern south east (SE2) regions are influenced strongly by storms embedded in the westerlies.

![Image of regions for which averages in tables are calculated. Central Australia is extended in such a way to include most of the arid regions.](image)

**Figure 3.15:** Regions for which averages in tables are calculated. Central Australia is extended in such a way to include most of the arid regions

### 3.8 Chapter conclusion

There are some obvious shortcomings in the MUGCM control simulation, particularly at high latitudes. In the Australian region the mean winds are displaced slightly to the east in winter and the eastern precipitation is too high. Over Australia, the MUGCM captures the pattern of near surface temperature well and the anomalies in magnitude compared to NCEP2 are well within the year-to-year variability of NCEP2 for the majority of the continent. The changes in precipitation are well within the range of other models. Overall, the MUGCM simulates the Australian climate reasonably well and can be used with some confidence in the experiments described in this thesis.
3. Model description, boundary conditions and mean climatology
Chapter 4

Simulated LGM and Present Day climate: I. Temperature and precipitation

4.1 Introduction

In the previous chapter the results from the MUGCM were compared with data, and the low-level atmospheric temperature compared favourably. While there were differences between the data and the model precipitation, these were no greater than in other AMIP models. In this chapter the mean temperature and precipitation results for the PD and the LGM, with particular emphasis on the Australian region, will be assessed more closely, and compared with both proxy evidence and other PMIP models.

These two model variables are intimately linked to proxy evidence. The simulated change from the PD climate to the LGM will be compared with the broad results from the proxy evidence.

The comparison between the different models allows a study of how they respond to the extreme boundary conditions for the LGM over Australia. Differences are shown globally, to best appreciate how the Australian changes fit into the global context. These results can be compared with Kageyama et al. (2001), who presents such a comparison concentrating on Europe and western Siberia.

The land extent shown is for the PD. The lower sea-level at the LGM reveals land around Australia, particularly to the south and north (Figure 2.1).
Globally, the changes are not great. The southern part of the South China Sea was land, as was the Bering Strait.

Figure 4.1: The land extent at the LGM (shaded). The PD continental outlines are also drawn.

The response of each of the models to the imposed boundary conditions will be influenced by the physics, resolution and parameterisations in the model. The different model resolutions and surface parameterisations will be assessed to determine how these link to the inter-model differences. This analysis implicitly tests how the MUGCM results compare with the other PMIP models, and if it is well-placed for later analysis of the LGM simulated climate. The names of the models and their institutions are shown in Table 4.1.

<table>
<thead>
<tr>
<th>Model</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUGCM</td>
<td>The University of Melbourne, Australia</td>
</tr>
<tr>
<td>BMRC2</td>
<td>Australian Bureau of Meteorology Research Centre</td>
</tr>
<tr>
<td>CCC2.0</td>
<td>Canadian Centre for Climate Modelling and Analysis</td>
</tr>
<tr>
<td>CCSR1</td>
<td>Center for Climate System Research, Japan</td>
</tr>
<tr>
<td>ECHAM3</td>
<td>University of Bremen, Germany</td>
</tr>
<tr>
<td>GEN2</td>
<td>Program for Climate Model Diagnosis and Intercomparison, USA</td>
</tr>
<tr>
<td>LMCELMD4</td>
<td>Laboratoire de Méteorologie Dynamique, France</td>
</tr>
<tr>
<td>LMCELMD5</td>
<td>Laboratoire de Méteorologie Dynamique, France</td>
</tr>
<tr>
<td>MRI2</td>
<td>Meteorological Research Institute, Japan</td>
</tr>
<tr>
<td>UGAMP</td>
<td>The UK Universities’ Global Atmospheric Modelling Programme</td>
</tr>
</tbody>
</table>

Table 4.1: The MUGCM and PMIP model names and institution

Table 4.2 shows the resolution of MUGCM and each of the PMIP models. Finer horizontal resolution will allow a greater potential to capture the correct regional variability of the surface features, while the vertical resolution will play a strong role in how well the boundary layer is represented. The MUGCM has
relatively high horizontal resolution, but it has relatively low vertical resolution, though its lowest level is much lower than some of the other models.

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Res</th>
<th># lon x lat</th>
<th>°lat x °lon</th>
<th>Levels</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUGCM</td>
<td>S R21</td>
<td>64x54</td>
<td>3.2x5.6</td>
<td>sigma 9</td>
<td>991</td>
</tr>
<tr>
<td>BMRC</td>
<td>S R21</td>
<td>64x56</td>
<td>3.2x5.6</td>
<td>sigma 9</td>
<td>991</td>
</tr>
<tr>
<td>CCC2.0</td>
<td>S T32</td>
<td>96x48</td>
<td>3.75x3.75</td>
<td>hybrid 10</td>
<td>980</td>
</tr>
<tr>
<td>CCSR1</td>
<td>S T21</td>
<td>64x32</td>
<td>5.6x5.6</td>
<td>sigma 20</td>
<td>995</td>
</tr>
<tr>
<td>ECHAM3</td>
<td>S T42</td>
<td>128x64</td>
<td>2.8x2.8</td>
<td>hybrid 19</td>
<td>996</td>
</tr>
<tr>
<td>GEN2</td>
<td>S T31</td>
<td>96x48*</td>
<td>3.75x3.75</td>
<td>hyb/sigma 18</td>
<td>993</td>
</tr>
<tr>
<td>LMCELMDB4</td>
<td>FD</td>
<td>48x36</td>
<td>sin(lat)x7.5**</td>
<td>sigma 11</td>
<td>979</td>
</tr>
<tr>
<td>LMCELMDB5</td>
<td>FD</td>
<td>64x50</td>
<td>sin(lat)x5.6**</td>
<td>sigma 11</td>
<td>979</td>
</tr>
<tr>
<td>MRI2</td>
<td>FD</td>
<td>72x46</td>
<td>4x5</td>
<td>hybrid 15</td>
<td>912</td>
</tr>
<tr>
<td>UGAMP</td>
<td>S T42</td>
<td>128x64</td>
<td>2.8x2.8</td>
<td>hybrid 19</td>
<td>996</td>
</tr>
</tbody>
</table>

R = rhomboidal; T = triangular; S = spectral; FD = finite difference
* 96x48 for AGCM and 180x90 for surface
** lmcelmd4 and lmcelmd5 are regular in sine of latitude and have constant area for each grid box

Table 4.2: Resolution of the models. The lowest level is in hPa. Information about the PMIP models is from http://www-lsce.cea.fr/pmip/

The surface parameterisations have an influence on the near surface temperatures and possibly precipitation. The response of surface fluxes has been examined for a number of off-line land surface schemes as part of the ‘Project for Intercomparison of Land Surface Parameterization Schemes’ (PILPS) (Henderson-Sellers et al., 1995). The intercomparison has been extended to include the response with the schemes coupled to GCMs, e.g. Guo et al. (2004). Aspects of the land surface schemes in the GCMs examined here are described in Table 4.3 which might help explain the range of response in the surface temperatures and precipitation. Changes in the surface scheme in studies of the LGM produce strong responses in the temperature. For example, Wyputta and McAvaney (2001) reconstructed LGM vegetation across Australia, which included an extension of dryland vegetation types, and after including LGM vegetation in place of PD vegetation in a version of the BMRC2 model, there was a further annual average cooling of 1-2°C across Australia.
4. Simulated LGM and Present Day climate: I. Temperature and precipitation

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Soil Scheme</th>
<th>Vegetation</th>
<th>Soil Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUGCM</td>
<td>2L</td>
<td>No explicit vegetation</td>
<td>1</td>
</tr>
<tr>
<td>BMRC</td>
<td>SLM</td>
<td>No explicit vegetation</td>
<td>1, land ice</td>
</tr>
<tr>
<td>CCC2.0</td>
<td>SLW</td>
<td>24 soil/vegetation types</td>
<td>1</td>
</tr>
<tr>
<td>CCSR1</td>
<td>SL</td>
<td>No explicit vegetation</td>
<td>1</td>
</tr>
<tr>
<td>ECHAM3</td>
<td>SLWB</td>
<td>3 vegetation types W</td>
<td>1, DB</td>
</tr>
<tr>
<td>GEN2</td>
<td>LSX</td>
<td>EVE vegetation model</td>
<td>6 soil layers</td>
</tr>
<tr>
<td>LMCELMD4</td>
<td>SL</td>
<td>No explicit vegetation</td>
<td>1</td>
</tr>
<tr>
<td>LMCELMD5</td>
<td>SECHIBA</td>
<td>7 vegetation types</td>
<td>1</td>
</tr>
<tr>
<td>MRI2</td>
<td>4L</td>
<td>no vegetation determined</td>
<td>1</td>
</tr>
<tr>
<td>UGAMP</td>
<td>3L</td>
<td>vegetation not specified</td>
<td>1</td>
</tr>
</tbody>
</table>

**Soil Schemes:**
- SLM = single layer bucket (McAvaney and Hess, 1996)
- SLW = single layer bucket (Wilson and Henderson-Sellers, 1985), also describes the vegetation
- SLWB = single layer bucket (Wilson and Henderson-Sellers, 1985; Blondin, 1989; Duemenil, 1993)
- SL = single layer bucket (Manabe et al., 1965; Manabe, 1969; Manabe and J.L. Holloway, 1975)
- 2L = 2 layer bucket, the upper layer responds to diurnal variations (Deardorff, 1977; Hunt, 1985)
- 4L = 4 layer soil model which can treat the freezing and melting process of soil moisture (Kistler et al., 1993)
- 3L = 3 layer diffusive model, no flux at the bottom of soil model (Dong and Valdes, 1995)
- LSX = Land Surface Transfer Scheme (Pollard and Thompson, 1995; Thompson and Pollard, 1995)
- SECHIBA described in Ducoudre et al., 1993

**Vegetation Schemes:**
- W = forest, other vegetation, no vegetation (+ land ice) (Wilson and Henderson-Sellers, 1985)
- EVE = EVE vegetation model. For 0k, it is driven by observed climate and closely reproduces observed distributions. It predicts 110 life forms. Referred to in: Felzer et al. (2000)
- 7 = 7 vegetation types and 1 bare soil type (Matthews, 1983)
- 24 = 24 soil/vegetation (each grid cell determined by a 2/3 and 1/3 weighting of primary/secondary vegetation type) (Wilson and Henderson-Sellers, 1985)

**Soil Types:**
- 1 = 1 soil type
- 6 = 6 soil layers with sand/silt/clay fractions from 1°x1° soil texture database (Cosby, 1984; Webb et al., 1993)
- DB = 1 soil type (Blondin, 1989; Duemenil, 1993)

Table 4.3: Land surface schemes of all models. Information about the PMIP models is from http://www-lsce.cea.fr/pmip/

4.2 Temperature

To allow for the different vertical resolution of the PMIP models, temperature is made available at a ‘reference’ level of 2 m (screen height). For ease of comparison, Figure 4.2 shows the annual 2 m LGM temperature anomaly for the MUGCM. The annual 2 m temperature anomaly for each of the PMIP models with prescribed LGM SSTs is presented in Figure 4.3.

Over the ocean the differences range spatially from increases of more than 2°C in the east Pacific and off the east coast of Australia to decreases of 10°C in the North Atlantic. The LGM minus PD anomalies of near-surface air temperature are significant almost everywhere in the MUGCM simulation (Fig-
4.2 Temperature

Figure 4.2: MUGCM annual LGM temperature anomaly at 2 m. Contours at -25, -15, -10, -5, -3, -2, -1, 0, 1, 2, 3, 5, 10°C, negative contours are dashed and the zero contour is bold. Differences significant at the 99% level are stippled.

Over the ocean the anomalies are similar between all models, including MUGCM, except BMRC2. The similarity is to be expected as the LGM SSTs are prescribed. The BMRC2 temperatures are about 1°C warmer than the other models in the Indian Ocean and near the dateline in the southern Pacific Ocean. The guidelines for the PMIP suggest using the 1979-88 AMIP data for SSTs and sea-ice for the PD, which most do. UGAMP and CCC2.0 use a SST climatology from Alexander and Mobley (1976), which is cooler than the SSTs suggested by PMIP. GEN2 used the SST climatology developed by Shea et al. (1992), based on the years 1950-1979. Compared to the climatology of Alexander and Mobley (1976), the Shea et al. (1992) Southern Hemisphere subtropics are warmer during summer, but the Southern Hemisphere is cooler south of 45°S all year round, thus this is the coolest SST climatology from all the models. The PD MUGCM simulation has Reynolds (1988) SSTs for the years 1982-1987 prescribed, which would be expected to be the warmest climatology, particularly in the eastern Pacific, as the time period includes a number of strong El Niños. For most of the models, the PD SST climatology will not have much influence on the near-surface temperature anomaly as the LGM SSTs are created by applying an anomaly to the PD climatology. Some models have used the CLIMAP SSTs directly (GEN2 and UGAMP), but the spatial pattern of annual 2 m temperature anomalies are still similar to the other models. The CLIMAP SSTs were also used directly in the MUGCM, with the seasonal cycle.
4. Simulated LGM and Present Day climate: I. Temperature and precipitation

Figure 4.3: LGM - PD Annual surface air temperature, PMIP simulations. Contours at -25, -15, -10, -5, -3, -2, -1, 0, 1, 2, 3, 5, 10°C, negative contours are dashed and the zero contour is bold.
Figure 4.3: Continued...
4. Simulated LGM and Present Day climate: I. Temperature and precipitation

Figure 4.3: Continued...
4.2 Temperature

from the PD simulation. The method used to create the LGM SSTs in BMRC2 is not specified, but the warmer anomalies suggest a treatment slightly different from the other models.

Over the region of LGM sea-ice there are differences between the models. All models except LMCELMD4 and 5 have anomalies over Antarctica and out across the LGM sea-ice of greater than 5°C. CCC2.0 and CCSR1 have anomalies of greater than 15°C over the sea-ice. These differences between the models do not reflect the differences in the dataset from which the PD ice is prescribed (all LGM sea-ice is from CLIMAP), thus the differences must be due to each model’s particular method for calculating the temperature over sea-ice.

Simulations with the LGM SSTs show that over almost all land surfaces the 2 m temperatures are lower than the PD simulation. Australia and the north of South America are the exception to this. Across Australia, whilst the majority of simulations show a cooling, some (CCSR1, ECHAM3, LMCELMD4,5 and UGAMP) show warming, particularly in the north of Australia. BMRC2 shows warming right across Australia; it also shows the greatest warming in the southern Pacific and Indian Oceans, which may well contribute to the higher temperatures across Australia.

<table>
<thead>
<tr>
<th>Model</th>
<th>Present Day</th>
<th>LGM</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUGCM</td>
<td>22.49</td>
<td>20.43</td>
<td>-2.06</td>
</tr>
<tr>
<td>BMRC2</td>
<td>23.08</td>
<td>23.74</td>
<td>0.65</td>
</tr>
<tr>
<td>CCC2.0</td>
<td>19.78</td>
<td>17.33</td>
<td>-2.46</td>
</tr>
<tr>
<td>CCSR1</td>
<td>24.48</td>
<td>22.04</td>
<td>-2.44</td>
</tr>
<tr>
<td>ECHAM3</td>
<td>23.80</td>
<td>22.43</td>
<td>-1.36</td>
</tr>
<tr>
<td>GEN2</td>
<td>21.84</td>
<td>18.24</td>
<td>-3.60</td>
</tr>
<tr>
<td>LMCELMD4</td>
<td>22.55</td>
<td>21.14</td>
<td>-1.41</td>
</tr>
<tr>
<td>LMCELMD5</td>
<td>22.56</td>
<td>21.34</td>
<td>-1.22</td>
</tr>
<tr>
<td>MRI2</td>
<td>22.50</td>
<td>21.54</td>
<td>-0.96</td>
</tr>
<tr>
<td>UGAMP</td>
<td>23.85</td>
<td>23.17</td>
<td>-0.69</td>
</tr>
</tbody>
</table>

Table 4.4: Annual 2 m air temperature (°C) over all of Australia (PD extent) for all models with PD and fixed SST LGM simulations

There is a considerable range amongst the models in the Australian long term annual mean temperature simulated for PD and LGM. To put a figure on the change, Table 4.4 shows the Australia wide average of the 2 m temperature for each of the different PMIP models, for the PD, LGM and the difference between the two. In order to discount the regions that are land in the LGM, but ocean in the PD simulations, the region examined is the PD land extent. The
4. Simulated LGM and Present Day climate: I. Temperature and precipitation

<table>
<thead>
<tr>
<th>Model</th>
<th>Summer (DJF)</th>
<th>Winter (JJA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Present Day</td>
<td>LGM</td>
</tr>
<tr>
<td>MUGCM</td>
<td>27.05</td>
<td>25.89</td>
</tr>
<tr>
<td>BMRC2</td>
<td>28.40</td>
<td>29.73</td>
</tr>
<tr>
<td>CCC2.0</td>
<td>26.09</td>
<td>23.94</td>
</tr>
<tr>
<td>CCSR1</td>
<td>31.46</td>
<td>29.41</td>
</tr>
<tr>
<td>ECHAM3</td>
<td>28.08</td>
<td>27.00</td>
</tr>
<tr>
<td>GEN2</td>
<td>27.76</td>
<td>24.79</td>
</tr>
<tr>
<td>LMCELMD4</td>
<td>28.65</td>
<td>27.50</td>
</tr>
<tr>
<td>LMCELMD5</td>
<td>28.00</td>
<td>26.92</td>
</tr>
<tr>
<td>MRI2</td>
<td>28.15</td>
<td>27.03</td>
</tr>
<tr>
<td>UGAMP</td>
<td>28.32</td>
<td>28.75</td>
</tr>
</tbody>
</table>

Table 4.5: Summer and Winter 2 m air temperature (°C) over all of Australia (PD extent) for all models with PD and fixed SST LGM simulations

PD observed annual average temperature is 21.6°C for the period 1952-1999. GEN2 is closest to this value, with all other models except CCC2.0 simulating temperatures that are too warm. CCSR1, ECHAM3 and UGAMP are all warmer than observed by more than 2°C. In general, the LGM simulations are cooler, by up to 3.6°C, however there is a range of responses, with BMRC2 showing a warming of 0.65°C. The MUGCM simulates a cooling across Australia at the LGM of 2.06°C. This is at the cooler end of the model results. The range of results for Australia show that, discounting the BMRC2 simulations which seemed to have extremely cool PD SSTs, all models are simulating a decrease in temperature, which matches the direction of change shown by proxy evidence. Thus the MUGCM is well placed within the range of PMIP AGCMs to simulate the mean near surface temperature of Australia at the LGM.

Table 4.5 show the Australia-wide average temperature for winter and summer for PD, LGM and their difference. The observed Australia-wide mean temperature for the years 1953-1999 is 15.1°C in winter and 27.3°C in summer. The range of seasonal values in the models is generally too warm in both summer and winter, like the annual values.

The reduction in temperature in winter is generally the greatest of all the seasons while summers are generally only slightly cooler than the PD. This means that the difference in temperature between winter and summer (‘seasonality’), increases in all models except CCC2.0 and LMCELMD4.

The increased seasonality means that the reconstruction of temperature from vegetation change (e.g. Singh (1983); Singh and Luly (1991); Kershaw (1986))
might reflect the greater winter cooling, rather than the annual average temperature. However, even allowing for the increased seasonality, the reduction in temperature in winter of even the coolest simulation is not as much as the temperature depression found by \cite{Miller1997} of 10°C or even the more modest temperature reduction inferred by \cite{Hope1983a} and \cite{Colhoun1985} of about 6°C.

4.3 Precipitation

4.3.1 Simulated MUGCM LGM precipitation

Proxy evidence suggests drier LGM conditions at most sites across Australia. The MUGCM LGM annual precipitation and anomalies from PD are presented in Figure 4.4. The anomaly (LGM-PD) plot shows both wetter and drier conditions over the oceans. Differences that are statistically significant at the 99\% level are shown with stippling. In the seasonal differences, shown in Figure 4.5 and 4.6, the increased precipitation corresponds closely with the pattern of anomalous warming in the CLIMAP SSTs. Over land there is increased precipitation associated with elevated topography due to the lowered sea-level and high ice-sheets on the Northern Hemisphere continents. Anomalously warm coastal SSTs result in increased rainfall that extends over the continents in places, for example near a warm spot off the Australian east coast in winter. Elsewhere across Australia there is generally a decrease in the precipitation, in winter and summer and in the annual average.

4.3.2 PMIP simulations of LGM precipitation

Precipitation is a highly variable quantity in both space and time, and is difficult to model accurately, as shown by the AMIP comparison \cite{Zhang2003}. The large scale results are reasonable over regions away from high topography, but the local amounts are often simulated poorly. One way to assess how well the MUGCM simulates LGM precipitation is to compare results with those from the other PMIP models with prescribed SSTs.

Figure 4.7 shows the annual precipitation differences between each model’s LGM and PD simulations. In the Atlantic all the models, including MUGCM, show a similar pattern of anomalies, with increases to the north and off central South America. In North America all of the models show an increase in
precipitation in the central western region. South America shows decreased precipitation with patches of increase. In the southern Pacific Ocean the warmer SSTs are reflected by enhanced LGM precipitation in the east and around the hot spot off the east coast of Australia. A similar consistent picture is shown in the eastern North Pacific. All the models show decreased precipitation in the tropical western Pacific - a signal not unlike that which occurs during El Niño. The El Niño-like response is echoed in many of the models in other parts of the globe also - such as drier conditions for Brazil and wetter conditions in the eastern equatorial Pacific.

Recent LGM results from oceanic cores have been described as ENSO-like (Beaufort et al., 2001; Müller and Hope, 2004), by which the authors mean that the indicators from these cores are similar to the state seen during an El Niño. Across Europe and central Asia there is a decrease in precipitation, except in LMCELMD4 and 5 which show increased precipitation right through to the Indian Ocean. The warm region in the CLIMAP SSTs in the northern Indian Ocean is reflected in increased rainfall for all models. All models also indicate increased precipitation on the east coast of Africa, extending inland by varying amounts.

All except MUGCM, BMRC2, CCSR1 and GEN2 show an increase in precipitation over the Indian sub-continent. This increase is most evident in JJA (not shown), across the north of India, indicating an increase in the strength of the northern monsoon in these models. This is an important difference between the models, as the Indian monsoon is of fundamental importance to the amount of rain throughout the sub-continent.

The Australian region has a consistent increase in rainfall off the east coast over the hot spot in the CLIMAP SSTs. MUGCM, BMRC2, CCC2.0, MRI2 and UGAMP all show a consistent decrease in precipitation across the Australian continent, while GEN2 has a consistent increase except in the very south.

Table 4.6 shows the areally weighted precipitation average over the PD land extent of Australia for each of the PMIP models and MUGCM. The PD mean rainfall is 1.2 mm day$^{-1}$ (for the years 1910-1999), with a standard deviation of 0.2 mm day$^{-1}$. The range of modelled PD annual mean rainfall amount is wide, with BMRC2 and CCC2.0 simulating totals close to observed, but MRI2 simulating 2.85 mm day$^{-1}$, and CCSR1 only 0.65 mm day$^{-1}$. In general the amount of rainfall simulated at the LGM is of the order of the present day simulation of the same model, but the percentage change varies from a positive
4.3 Precipitation

Figure 4.4: MUGCM annual LGM Precipitation. (a) Mean. (b) Anomaly from the PD. Contours at -13, -10, -8, -5, -2, -1, -0.5, 0, 0.5, 1, 2, 3, 8, 10, 13 mm/day. Negative contours are dashed, zero contour bold. Regions of difference significant at the 99% level are stippled.
4. Simulated LGM and Present Day climate: I. Temperature and precipitation

Figure 4.5: As Figure 4.4 but for JJA
4.3 Precipitation

Figure 4.6: As Figure 4.4 but for DJF
4. Simulated LGM and Present Day climate: I. Temperature and precipitation

Figure 4.7: LGM - PD annual precipitation, PMIP simulations. Contours at -20, -16, -13, -10, -8, -5, -2, -1, -0.5, 0, 0.5, 1, 2, 5, 8, 10, 13, 16, 20 mm/day. Negative contours are dashed and the zero contour is bold
Figure 4.7: Continued...
4. Simulated LGM and Present Day climate: I. Temperature and precipitation

Figure 4.7: Continued...
change of 38% for GEN2, through small negative changes for LMCELMD4 and 5, CCSR1 and ECHAM3 to a drying at the LGM of 54% for BMRC2.

<table>
<thead>
<tr>
<th>Model</th>
<th>Present Day</th>
<th>LGM</th>
<th>Difference</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUGCM</td>
<td>1.78</td>
<td>1.43</td>
<td>-0.35</td>
<td>-20</td>
</tr>
<tr>
<td>BMRC2</td>
<td>1.18</td>
<td>0.54</td>
<td>-0.64</td>
<td>-54</td>
</tr>
<tr>
<td>CCC2.0</td>
<td>1.19</td>
<td>0.93</td>
<td>-0.26</td>
<td>-22</td>
</tr>
<tr>
<td>CCSR1</td>
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<td>0.58</td>
<td>-0.07</td>
<td>-11</td>
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<tr>
<td>ECHAM3</td>
<td>1.82</td>
<td>1.62</td>
<td>-0.20</td>
<td>-11</td>
</tr>
<tr>
<td>GEN2</td>
<td>0.69</td>
<td>0.95</td>
<td>0.26</td>
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<td>LMCELMD5</td>
<td>1.45</td>
<td>1.40</td>
<td>-0.04</td>
<td>-3</td>
</tr>
<tr>
<td>MRI2</td>
<td>2.84</td>
<td>2.35</td>
<td>-0.49</td>
<td>-17</td>
</tr>
<tr>
<td>UGAMP</td>
<td>1.12</td>
<td>0.79</td>
<td>-0.33</td>
<td>-29</td>
</tr>
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</table>

Table 4.6: Australian annual precipitation for PD, LGM and anomaly (mm day$^{-1}$)

<table>
<thead>
<tr>
<th>Model</th>
<th>Present Day</th>
<th>LGM</th>
<th>Diff</th>
<th>Present Day</th>
<th>LGM</th>
<th>Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUGCM</td>
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<td>2.19</td>
<td>-0.84</td>
<td>1.10</td>
<td>1.13</td>
<td>0.03</td>
</tr>
<tr>
<td>BMRC2</td>
<td>1.85</td>
<td>1.13</td>
<td>-0.72</td>
<td>0.70</td>
<td>0.40</td>
<td>-0.30</td>
</tr>
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<td>CCC2.0</td>
<td>2.27</td>
<td>2.08</td>
<td>-0.20</td>
<td>0.81</td>
<td>0.84</td>
<td>0.03</td>
</tr>
<tr>
<td>CCSR1</td>
<td>0.77</td>
<td>0.96</td>
<td>0.19</td>
<td>0.87</td>
<td>0.47</td>
<td>-0.40</td>
</tr>
<tr>
<td>ECHAM3</td>
<td>4.25</td>
<td>4.46</td>
<td>0.21</td>
<td>0.53</td>
<td>0.28</td>
<td>-0.26</td>
</tr>
<tr>
<td>GEN2</td>
<td>1.59</td>
<td>3.04</td>
<td>1.46</td>
<td>0.79</td>
<td>0.30</td>
<td>-0.49</td>
</tr>
<tr>
<td>LMCELMD4</td>
<td>3.75</td>
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<td>-0.45</td>
<td>1.81</td>
<td>2.12</td>
<td>0.31</td>
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<td>0.93</td>
<td>0.97</td>
<td>0.03</td>
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<tr>
<td>MRI2</td>
<td>5.10</td>
<td>4.56</td>
<td>-0.54</td>
<td>1.96</td>
<td>1.57</td>
<td>-0.39</td>
</tr>
<tr>
<td>UGAMP</td>
<td>3.17</td>
<td>2.88</td>
<td>-0.30</td>
<td>0.71</td>
<td>0.38</td>
<td>-0.33</td>
</tr>
</tbody>
</table>

Table 4.7: Australian Summer and Winter precipitation in mm day$^{-1}$ (present day extent) for MUGCM and each model

The summer and winter Australia-wide average precipitation is 1.9 mm day$^{-1}$ and 0.8 mm day$^{-1}$ respectively (for the years 1910-1999). The Australia-wide precipitation from MUGCM and each of the PMIP models with fixed SSTs is shown in Table 4.7. BMRC2 and UGAMP are the only two with precipitation decreases in all four seasons (spring and autumn are not shown). MUGCM has the largest decrease, with a drop of 1.11 mm day$^{-1}$ in autumn. This range of responses shows how difficult it is to correctly simulate precipitation. Unlike the consistent enhanced seasonality in temperature (greater cooling in winter, with
4. Simulated LGM and Present Day climate: I. Temperature and precipitation

less relative cooling in summer), there is no consistent change in the seasonality of the LGM precipitation change from the PD amongst the models.

4.4 Discussion

From the temperature and precipitation results shown above it is clear that most models simulate the PD Australian climate reasonably well. CCSR1, however, has very little PD Australia-wide rainfall and does not show the appropriate seasonal cycle. The direction of change in the LGM simulation is another way of assessing the capacity of the model to respond to the extreme LGM boundary conditions. Proxy evidence suggests cooler and drier Australia-wide conditions. GEN2 shows an increase in annual rainfall while BMRC2 shows an increase in mean annual temperature. The results from these three models should be examined with caution.

After examining the response of the models to the LGM forcing, some suggestions as to the reasons for the differences between the models can be posed. UGAMP and ECHAM3 have the highest horizontal resolution, and their maps in Figure 4.3 show greater horizontal structure in the anomalies. One aspect to note is the extended anomalous warming down the north east Australian coast that is not evident in other models and is probably due to grid boxes in this location becoming ocean in the LGM simulation, whereas for the coarser models they would remain as land (see Figure 4.1). This anomaly in the temperature is reflected in the precipitation anomaly. Away from the coastlines, the anomalies are similar between these models with higher resolution and other models. The range of vertical resolution and height of the lowest model level does not show a direct link to the Australia-wide surface temperature or precipitation response, although it may have consequences for the surface scheme.

GEN2 is the only PMIP model that allows vegetation types to respond to the climatic conditions in the model, and it also simulates the coolest response to the LGM conditions, as suggested by the study of Wyputta and McAvaney (2001). CCC2.0 also shows a cooler atmosphere for both the PD and LGM, and it has the highest number of vegetation types prescribed. Most other models do not have varied vegetation types and their surface response depends on the parameterisation of their soil scheme.

Kubatzki and Claussen (1998) found that the albedo of deserts is very important: with bright deserts the biome model linked to the ECHAM GCM extends
4.4 Discussion

the desert area, while initialising the GCM with forest and ‘darker’ deserts leads to further forest growth. These responses will have large impacts on the surface temperature. From the PMIP web-site it is evident that only GEN2 does not have prescribed albedo. Thus the amount of sensible heat available at the surface can be strongly tuned. It would be expected that the models with vegetation (GEN2, CCC2.0, ECHAM and LMCELMD5) will have more varied albedo, which might better reflect the observed range of surface conditions. GEN2 and CCC2.0 show strongly cooler atmospheres than the other models in the Australian region (Table 4.4), but LMCELMD5 and ECHAM are within the range of other models. MUGCM does not have vegetation but its albedo responds to the level of moisture in the soil (Hunt 1985), thus as the soil dries at the LGM, the albedo increases, possibly leading to enhanced cooling. The MUGCM exhibits one of the larger amounts of Australia-wide cooling between the PD and LGM (Table 4.4).

The warming seen over Australia in the BMRC2 model at the LGM (Figure 4.3(a) and Tables 4.4 4.5) may be linked to the relatively warm ocean temperatures in the Indian Ocean and the Pacific near the dateline. However, the warming over land is greater than would be expected from the relative warmness of the ocean. A likely explanation is that, although many of the other models also use a single layer bucket model (Table 4.3), McAvaney and Hess (1996) state that the BMRC2 model in particular has a lack of resistance to the soil moisture bucket drying, leading to errors in the partitioning between latent and sensible heat at the surface. This error is not as great across the Northern Hemisphere continents because of the extensive ice-sheet cover at the LGM, where ice has a different parameterisation for the partitioning of surface fluxes. Decreased precipitation across Australia at the LGM would encourage the soil moisture bucket to be even drier than in the PD simulation, leading to warming at the LGM. There would also be a positive feedback between the decreased latent heat and subsequent precipitation decrease, enhancing the known memory in the system (Simmonds and Hope 1997 1998); this would be particularly true in summer (Table 4.7), where the recycling of moisture evaporating from the surface of tropical Australia into future precipitation is high (Hope et al. 2002).

The models with a number of levels in their soil moisture scheme, but no vegetation (MUGCM, MRI2 and UGAMP), are among those with a drier response across Australia at the LGM (Table 4.4). MRI2 and UGAMP also have
the least cooling, after BMRC2, which may suggest that their soil schemes are too efficient at drying, particularly under drier conditions. Once dry, the latent heat release will be reduced and the surface will warm - as was evident in the strong warming seen in BMRC2.

4.5 Chapter summary and conclusions

After assessing the mean precipitation and temperature fields it was clear that CCSR1 did not simulate the seasonal cycle of PD precipitation correctly and GEN2 and BMRC2 responded to the LGM boundary conditions contrary to what the proxy evidence suggests. All the other models show consistent responses in 2 m temperature across Australia, with widespread cooling, although some models had warming in the north. The simulated LGM response is not as cool as the temperatures reconstructed from proxies. The precipitation means and anomalies showed a wider range between models (discounting the three outlined above), although all showed a decrease in the annual, all-Australia mean.

The MUGCM, and most of the PMIP models show cooling across Australia in most seasons, with more in winter than summer. There is no consistent shift in seasonality of the simulated LGM precipitation response across Australia.

The horizontal resolution of the models had little bearing on the mean near surface climate. The surface schemes, however, including vegetation, surface albedo and the level of resistance of the soil moisture, all have a strong influence on the precipitation and near surface temperature simulated and the differences to the LGM.

The Australia-wide differences between the LGM and the PD as simulated by the MUGCM are within the range of the response shown by other models but at the cooler and drier end of the range. For examination of high frequency data from the model in later Chapters, the MUGCM will be used, and this comparison of the surface variables with PMIP models show that it is well placed for the task.
Chapter 5

Simulated LGM and PD climate: II Winter circulation

5.1 Introduction

The responses in the simulations of the mean near-surface climate variables for the PD and LGM were considered in the previous chapter. The MUGCM and all but one of the PMIP models show an annual average cooling across Australia at the LGM, and all but one are drier in the Australia-wide annual mean. In southern Australia, a region where rainfall is dominated by rain-bearing storms in the westerlies, all the models but LMCELMD4 and 5 show a decrease in simulated precipitation at the LGM. The aim of this Chapter is to assess if the precipitation decline shown by the models is due to a shift in the winter fronts and storms that bring rainfall to southern Australia. A range of techniques to describe the storms are used with the MUGCM results and then mean characteristics are compared across the PMIP simulations.

Mid-latitude systems are driven by regions of baroclinicity, and thus respond to large-scale re-distributions of temperature around the globe, as at the LGM. At the LGM there was extensive cooling at the mid to high latitudes in the Northern Hemisphere due to the ice sheets on the Northern Hemisphere continents, which would modify the temperature gradients in that hemisphere markedly. This, coupled with the increased altitude of the ice-sheets, was found to drive the storms equator-ward in the Northern Hemisphere for LGM simulations examined by Kageyama et al. (1999b). The shifts in the baroclinic zones and storm tracks in the PMIP results was considered of great importance.
and has been studied at length for the Northern Hemisphere (Hall et al., 1996; Kageyama et al., 1999a,b; Dong and Valdes, 2000).

For the Southern Hemisphere, there are conflicting opinions about the shifts in the westerlies. Conceptual models, based on the proxy evidence from lake levels, pollen, dunes and dust plumes, suggested both northward and southward shifts in the westerlies (Heusser, 1989; Markgraf, 1989; Markgraf et al., 1986; Hesse, 1994; Shulmeister et al., 2004). The extended sea-ice in the Southern Hemisphere was believed to have driven an equator-ward shift in the westerlies (Harrison and Dodson, 1993).

Modelling studies found that there was a southward shift in the westerlies (Hubbard, 1995a; Wyrwoll et al., 2000; Wardle, 2003; Wyrwoll et al., 2000) explored shifts in the westerlies in the Southern Hemisphere with one of the PMIP models. They used a number of different indicators to assess the shift in the storm tracks, and found a southward shift, with regional variation. Some of these indicators are described below, including the shift in mean zonal wind and the Eady growth rate, which indicates regions of mid-latitude storm growth potential. Hubbard (1995a) also found a southward shift in the Southern Hemisphere westerlies in an LGM simulation using an early version of CCM1, one of the PMIP models, though not one examined in this thesis. He used the difference in the sea-level pressure averages, and a subjective assessment of the shift in a stylised ‘circulation’ (presumably from the average near-surface wind fields) to judge the shift in the westerlies.

The simulated results from the MUGCM are considered in this chapter, and are not linked back to the proxy evidence at this stage, but the reconstructed LGM lake-levels in southern Australia will be considered in the Chapter 6 and the direct proxies for changes in the circulation, the dune-fields, and their orientation, will be considered in Chapter 8. The mean response in the PMIP models will also be examined.

5.2 Circulation descriptors

5.2.1 Definitions of ‘westerlies’

The mean annual low level winds for the PD and LGM simulations and their difference are shown in Figure 5.1 and the zone of westerly winds can clearly be seen encircling Antarctica. During winter (Figure 5.2) the westerlies move
5.2 Circulation descriptors

north and over southern Australia. In the literature, the ‘westerlies’ are defined in many ways, beyond simply the band of mean near surface winds blowing towards the east. Each method can tell a subtly different story about the circulation. Methods may be used to determine the influence of storms at the surface, or to better understand the dynamics of the atmosphere, (Paciorek et al., 2002). Often the westerlies are described by features aloft, such as storm tracks and jets (Trenberth, 1991). The interest here is in systems bringing rainfall to southern Australia in winter. Thus the methods used to define the shifts in the ‘westerlies’ must correspond reasonably closely with rainfall over southern Australia.

(a) PD

(b) LGM

(c) LGM-PD

Figure 5.1: Annual mean low level winds from MUGCM for (a) PD, (b) LGM and (c) the anomaly. The reference vector is shown (ms$^{-1}$)

Features aloft are linked to synoptic systems near the surface, but may be offset equator-ward by 5-10$^\circ$ of latitude (Paciorek et al., 2002). For example, in the Australian region in winter, the climatological position of the subtropical jet crosses the west coast of Australia north of 20$^\circ$S, the eddy statistics at about 500 hPa are south of the jet (Trenberth, 1991), and the surface cyclone statistics are south of that (Simmonds and Keay, 2000). This shift has been found in
5. Simulated LGM and PD climate: II Winter circulation

![Figure 5.2](image-url)  
(a) PD  
(b) LGM  
(c) LGM-PD

**Figure 5.2:** JJA mean low level winds from MUGCM for (a) PD, (b) LGM and (c) the anomaly. The reference vector is shown (ms$^{-1}$)

Theoretical studies also ([Hoskins and Valdes, 1990](#)). Thus near-surface cyclone features might have the best link with the location of the precipitation falling from the systems, but the measures of the storm-tracks aloft will reveal a great deal about the potential for storms.

A number of different measures of the westerlies and related features are described below, including a number of measures linked to the surface as well as some linked to features aloft. The winter circulation is more important to rainfall across southern Australia, and will thus be the emphasis in this chapter. The mean features associated with the circulation will be examined first: the sea-level pressure, the zonal wind, and the zonally averaged temperature and stream function. Then a measure of the instability of the middle troposphere will be examined, followed by measures of surface cyclone activity.

### 5.2.2 Sea-level pressure

A first step to describing in detail the shifts in the circulation is to compare how the average winter pressure field has changed between the PD and LGM
MUGCM simulations. The high pressure region over Australia has strengthened considerably at the LGM (Figure 5.3). Storms and low pressure systems would be expected to track to the south of the climatological high pressure cell, and a mean increase in pressure may also correspond to a decrease in the number of low pressure systems crossing the region. Hence it is less likely that there would have been as many rain-bearing systems crossing the south of Australia.

The expansion of the high pressure cell over Australia is consistent with the LGM circulation suggested by Cupper (2003) as an explanation for his proxy results from playa lakes at the edge of the arid zone in south east Australia. He found evidence of shore-line dunes developing at either end of the playas, and, establishing a chronology for the activity via multi-proxy dating, he found that the circulation that might best explain his results at the LGM was for an expanded climatological high. This also aligns with what Rognon and Williams (1977) suggested. Iriondo (1999) also suggested an expanded climatological high, but he had it extending into the southwest, while it contracted northward in the east.

The LGM winter sea-level pressure anomaly map in Figure 5.3 shows that the positive anomaly affecting the south of Australia extends across into the southern Indian Ocean, the Tasman Sea and south to Antarctica. Away from the Australian region the pressure is lower. This pattern highlights that the shift in the westerlies affecting southern Australia is not simply the result of a hemispheric southward shift, but that there is considerable longitudinal asymmetry.

In many ways the anomaly is reminiscent of an El Niño pattern. It is well known that most of Australia has a higher probability of being dry during El Niños (McBride and Nicholls 1983; Zhang and Casey 1992), although that relationship can change over time (Nicholls et al. 1996). This indicates that the Walker circulation may be weaker than in the PD, and thus drier conditions might be expected in Australia due to more El Niño-like conditions. The LGM sea surface temperature (SST) anomaly across the tropical Pacific may explain this weakening of the Walker circulation, with a flattening of the zonal temperature gradient (Figures 3.12 and 3.13). This is similar to the experiments by Simmonds et al. (1989), where they removed the zonal gradients in SST around the globe, resulting in a ‘flattening’ of the SST gradient across the tropical Pacific. The result of their experiment was increased pressures across the Australian region also. In the vertical cross-section of the zonal wind from
Figure 5.3: JJA MUGCM Sea-level pressure for (a) PD, (b) LGM and (c) LGM minus PD. Contour interval is 4 hPa for mean fields and 2 hPa for the anomaly, negative contours are dashed. Stippling on the anomaly indicates differences significant at the 99% level.
5°S to 5°N along the equator in Figure 5.4, for the MUGCM PD simulation, the Walker circulation across the Pacific (between 150°E and 330°E) can be clearly seen, with strong westerly motion aloft, and strong return flow near the surface - the Tradewinds. At the LGM it can be seen that the winter Walker circulation is indeed much weaker. The anomaly plot (Figure 5.4(c)) shows this weakening well, with a reduction in both the westerly and easterly flow. A weakened Walker circulation leads to a reduction in the flow of moisture laden air over Australian longitudes, and thus a reduced capacity for rainfall, as observed during modern El Niño events. In the LGM simulation, the expected rainfall reduction is offset to some extent by the ‘hot-spot’ in the CLIMAP SSTs off the east coast of Australia.

5.2.3 Mean zonal wind

The mean westerly wind in the mid-latitudes is linked to the location of the storm tracks. The maps of zonal wind at 850 hPa from the MUGCM for winter at the LGM and PD are shown in Figure 5.5 on a polar stereographic projection to best appreciate the circumpolar trough. There are major differences between the two periods in the mid to high southern latitudes, particularly in winter and spring (not shown). The most marked change in the westerly belt is the new maxima in the Pacific Ocean east of the dateline in winter and spring. The northerly extent of the westerly belt has also contracted in the west of the Pacific and across the Australian continent in both these seasons. Elsewhere the westerlies look similar in both epochs, though there appears to be a northward extension of westerlies just upwind of the Andes - perhaps in response to the higher orography resulting from the lowered sea-level. The tropical easterlies (Trade winds) also show differences between the LGM and PD, with stronger meridional gradients in the south Atlantic and Indian Oceans at the LGM in winter and spring but a distinct weakening of the easterlies and their gradients in the southern Pacific Ocean. Over southern Africa there is a general weakening of both the westerlies and easterlies in all seasons. The changes in the zonal wind at 850 hPa between the PD and the LGM indicate that the winter and spring winds over New Zealand would be much stronger. The distinct southward shift in the westerlies crossing Australia clearly have implications for the climate, and in particular the rainfall regime, of southern Australia.
Figure 5.4: JJA zonal wind, meridionally averaged between 5°S and 5°N. (a) PD and (b) LGM MUGCM simulation (Contour interval 5 ms\(^{-1}\)), and (c) difference (Contour interval 2 ms\(^{-1}\))
5.2 Circulation descriptors

(a) PD, JJA

(b) LGM, JJA

(c) LGM-PD, JJA

Figure 5.5: Southern Hemisphere 850hPa zonal winds for each season in the (a) PD, (b) LGM MUGCM simulation, and their (c) difference. Contour interval: 2 ms$^{-1}$
5.2.4 Zonally averaged temperature and stream function

It was seen that the Walker circulation was weaker in the LGM simulation, explaining the pressure changes across the Pacific. The southward shift in the zonal wind in the Australian region noted above might be linked to a change in the meridional general circulation, the Hadley cell. To explore this the hemispherically averaged temperature and meridional mass stream function are analysed. When averaged over long periods, and over the hemisphere, the streamlines of the meridional mass stream function describe the mean overturning of mass (see Peixoto and Oort (1992), Figure 7.19 and associated equations, for a full explanation).

The SSTs will have a strong influence on the temperature structure of the atmosphere. They will be similar across all PMIP models with prescribed SST simulations. The anomaly pattern for August (Figure 3.13) shows a strong cooling approximately 10° north and south of the equator, then, in the Southern Hemisphere there is warming between the tropics and about 55°S and then distinct cooling pole-ward of 55°S, as the LGM simulation is sea-ice This may lead to a weakened and meridionally extended Hadley circulation in the Pacific.

The MUGCM LGM atmosphere was cooler than the PD throughout the troposphere (Figure 5.6), however the latitudinal structure of the cooling also suggests a weakening and pole-ward extension of the Hadley circulation. In the tropics and sub-tropics there is little cooling compared to the mid-latitudes. However, the gradient in temperature change shows a weakening of the temperature gradient from the tropics to the sub-tropics, particularly aloft (e.g. 250 hPa). The cooling in the tropics suggests less energy to drive the Hadley circulation while the greater cooling aloft in the tropics compared to the sub-tropics produces a weakened meridional temperature gradient, with less cooling of the southward branch of the Hadley cell aloft, and thus a potential pole-ward extension of the cell. Pole-ward of 42°S the cooling at the LGM is again strong, producing an enhanced meridional temperature gradient at the latitudes of the westerlies, which would result in more vigorous storms. Averaging over Australian longitudes, the anomalies are similar to the global zonal average.

A weaker Hadley circulation in the LGM simulation is also illustrated by the differences seen in the mass stream function (Figure 5.7). The gradients are much greater and the lowest value much lower in the PD. The return flow from a weaker winter Hadley circulation would be less vigorous, resulting in
weaker Pacific Trade winds (as seen in the plots of low level mean annual wind in Figure 5.1), and is consistent with the weakening of the Walker circulation discussed earlier. The greater pole-ward extent of the Hadley circulation would push the westerlies further south. In the Pacific the SST gradient from about 30°S to the ice would greatly enhance the baroclinicity in this region, producing the LGM zonal wind maximum seen in the eastern Pacific in winter in Figure 5.5(b).

5.2.5 Measures of baroclinicity

As discussed above, the westerlies can be defined by regions of high atmospheric instability or eddy activity, although these regions may be offset from the surface cyclones. Examining the Eady growth rate will provide an appreciation of the change in the magnitude and location of the potential for storm growth in a baroclinic environment between the PD and LGM simulations. Lindzen and Farrell (1980) show that the Eady growth rate is a useful measure of the faster growing disturbances generally. It was used by Hoskins and Valdes (1990) to examine the perpetuating nature of storm-tracks in the Northern Hemisphere, and Wyrwoll et al. (2000) as a measure of the storm track location in the Southern Hemisphere in a PD and LGM simulation.

The Eady growth rate is defined as \( 0.31f/N|\delta v/\delta z| \), where \( f \) is the Coriolis parameter and \( N \) is the Brunt-Väisälä frequency, (a measure of the static stability). Here the 500 hPa Eady growth rate was calculated using MUGCM PD and LGM results for winter, as in Wyrwoll et al. (2000). Temperature and wind data from the model levels above and below 500 hPa were used in the calculation. Figure 5.8 shows that in the PD there is a region of high Eady growth rate across southern Australia and across the Indian Ocean and southern Africa, while at the LGM the values are lower, and the maxima have shifted to the south of Africa, the central Pacific and into the south Atlantic. The main region of high Eady growth rate has shifted south, particularly on the continents. The centre of maximum Eady growth rate to the north west of New Zealand remains almost unchanged. In the Australian region there is much reduced potential for the growth of instabilities in the LGM compared to a very strong region of growth rate in the PD simulation.

The Eady growth rate may be further modified by changes in the moisture environment in the LGM atmosphere: Emanuel et al. (1987) found that the
Figure 5.6: JJA zonally averaged temperature from the (a) PD and (b) LGM MUGCM simulation (Contour interval 5 K), and difference (c) (Contour interval 1 K)
5.2 Circulation descriptors

Figure 5.7: JJA zonally averaged meridional mass stream function for (a) PD, (b) LGM from the MUGCM simulation. Contour interval: $20 \times 10^9$ kgs$^{-1}$. The difference (c) has a contour interval of $10 \times 10^9$ kgs$^{-1}$.
Figure 5.8: JJA Eady growth rate at 500 hPa, the contour interval is day$^{-1}$. (a) is PD, (b) LGM and (c) the difference, with differences significant at the 99% level stippled.
effects from condensation can increase the growth of baroclinic modes in their model, and those effects might be included in the Eady growth rate through changes to the static stability ([Hoskins and Valdes](Hoskins%20and%20Valdes%201990)). If the LGM atmosphere were drier this would further reduce the capacity for storm development, however this will not be explored further here.

The shifts in the Eady growth rate between the PD and LGM highlight not only a southward shift in the westerlies but also a longitudinal shift in the centres of storm activity. ([Kageyama%20et%20al.](Kageyama%20et%20al.%201999b)) found similar longitudinal shifts in the storm tracks of the Northern Hemisphere in PMIP LGM simulations.

### 5.2.6 Automatic cyclone identification and tracking

The analysis of the mean fields has suggested that the LGM has a weakening of both the Hadley and Walker circulations, as well as a weakening and shift in the region of greatest potential storm growth in the Australian region. All of these features of the LGM environment suggest a lower potential for the formation of rain-bearing storms across southern Australia. A perhaps more intuitive method of linking the rainfall and the storms is to look to identify and track the surface storms directly. There are some shortcomings with this link also, as the frontal systems associated with the mid-latitude cyclones are often the feature that brings rainfall to southern Australia.

Long-term average maps of the statistics of storms and their location have been used extensively as an alternative method to describe the westerlies ([Jones and Simmonds](Jones%20and%20Simmonds%201993); [Sinclair](Sinclair%201997); [Simmonds%20and%20Keay](Simmonds%20and%20Keay%202000)). The automatic cyclone identification and tracking scheme of ([Murray%20and%20Simmonds](Murray%20and%20Simmonds%201991)) was used here to locate closed and open low centres in both the control and LGM simulations.

Figure 5.9 shows the climatological average of the number of systems per area for the PD and LGM simulations for winter. The LGM average is not as smooth as that for the PD, possibly due to fewer years being used in the analysis (6 compared to 10). The circumpolar trough is evident in both the PD and LGM simulations, and, for the most part, the centres of maximum system density are in similar locations. There is no clear meridional shift in the system density in the circumpolar trough. Over southern Australia there are more cyclones at the LGM than in the PD. This is the case for all seasons. To the south of Australia the numbers are reduced in winter (Figure 5.9) and...
spring (not shown), but in summer there is little change, while in autumn there is some increase.

The automatic cyclone identification and tracking scheme can also be used to find anti-cyclones. The climatological mean location of these can be used to identify the latitude of the subtropical ridge. Wardle (2003) defined the westerlies as ‘...winds pole-ward of latitudes that correspond to the maximum anticyclone system density.’ This method of defining the westerlies provides a different approach than examining the regions of baroclinic instability, eddy activity or direct identification of the cyclones. Wardle (2003) applied the method to MUGCM output for the PD and LGM, and then found the latitude of maximum anti-cyclone system density for each longitude. The technique of finding the latitude of the maxima along a longitude line is similar to the method used to locate the subtropical ridge in raw data, as reviewed by Drosdowsky (2005). Drosdowsky (2005) describes some of the problems with this technique, which include multiple, or broad, maxima along a longitude line, and this would likely be a consideration for the technique used with anti-cyclone system density maps. Nonetheless, the results of Wardle (2003) are quite clear, with a distinct southward shift in the maxima of the anti-cyclone system density at the LGM, along Australian and Indian Ocean longitudes. This result is much clearer than that found identifying the cyclones directly, which suggested little southward shift.

The cyclone system density results may seem at odds with the results from the shift in anti-cyclone maxima, the latitudinal shifts in the zonal winds and the reduction in Eady growth rate over southern Australia. Other aspects of the cyclones, such as measures of their ‘strength’ may be more attuned to the large-scale environment. A number of different measures of cyclone strength have been described in Simmonds and Keay (2000), and include the intensity, radius and depth. The Laplacian of the pressure at the centre of a cyclonic system is used as an indication of the intensity of the system, while the size of the system is important to its strength also - larger systems will have a greater effect at the surface. Combining measures of the size and intensity of the system are defined by Simmonds and Keay (2000) as the ‘depth’ of the system. On a flat field, an axially symmetric parabolic depression with radius $R$, will have a depth defined as: $D = \frac{1}{4} R^2 \nabla^2 p$, where $p$ is the mean sea-level pressure. For non axially symmetric depressions the radius is determined by following lines radially from the cyclonic centre while $\nabla^2 p$ remains positive.

The depth is found to correlate better with the rainfall in southern Australia.
than the system density (Simmonds et al., 2001), with stronger systems linked to higher rainfall. The three measures of cyclone strength described above are shown from data by Simmonds and Keay (2000). The climatological winter map of intensity shows high values near the pole, becoming lower equator-ward, but only over the oceans. There is a reduction in intensities around South America. The radius of the cyclones in the data is largest in the ocean basins. In the Australian region the maxima are in the Tasman Sea and to the south of western Australia. The depth of the cyclones in winter is greatest around Antarctica, except along the Antarctic peninsula. Near Australia the regions of greater depth are over Tasmania and just south of Western Australia and in the Bight.

The winter cyclone depth for the LGM minus that for the PD across southern Australia is shown in Figure 5.10. There are increases in depth at the LGM in the Tasman and a small region to the southwest of Australia, but across the continent and to the south there is a marked decrease at the LGM. Thus, although there are more low pressure systems found by the cyclone tracking scheme for the LGM compared to the PD, the cyclones are weaker. Since the depth of the cyclones correlates better with the rainfall across southern Australia, the weaker systems seen here at the LGM might be expected to bring less rainfall.

### 5.3 Shift in zonal wind simulated by PMIP models

The sensitivity of the circulation to the LGM boundary conditions shown by the MUGCM is similar to that found by Wyrwoll et al. (2000). To assess the range of responses with different PMIP models and resolution, the basic field of the surface wind is plotted and the zero line separating the easterlies and westerlies can be easily seen. For comparison, the winter 10 m zonal wind averages for MUGCM is shown in Figure 5.11. This 10 m wind is calculated with a roughness length appropriate for a sandy surface, which is much lower than the standard roughness length over land. It is, however, consistent across the land surface, and thus comparisons can be made between the PD and LGM simulations. The main features compare closely with the 850 hPa level features (Figure 5.5(a) and 5.5(b)), though the line across Australia is further south for winds closer to the surface. The anomaly plot highlights the contraction and
Figure 5.9: JJA Cyclone System Density, MUGCM (a) PD and (b) LGM. The contour interval is 0.5, 1, 2, 4, 6, 10 \times 10^{-3} \text{ cyclones(°lat)}^{-2}. The contour interval for the anomaly (c) is 1 \times 10^{-3} \text{ cyclones(°lat)}^{-2}, and differences significant at the 99% level are stippled.
5.3 Shift in zonal wind simulated by PMIP models

Figure 5.10: Winter cyclone depth, (a) PD, (b) LGM and (c) the anomaly. Contour interval is 1 hPa, negative anomalies are dashed. The contours are missing in regions with no cyclones. Differences significant at the 99% level are stippled.
intensification of the westerlies.

Although not as complex as a number of the measures of the westerlies described above, it can be shown that the mean zonal wind, and its shifts in the latitude of zero line between the easterlies and westerlies in the subtropics is closely linked to south Australian rainfall. Figure 5.12 shows the winter rainfall (gridded from station data) averaged across the south west of Australia (an area that receives the majority of its rainfall from fronts from the west) along with the latitude of the zero line in the NCEP2 mean winter 10 m zonal winds (averaged from 110-130°E) from 1979-2000. The peaks and troughs of the two curves are strikingly similar, with southward shifts in the zero line closely linked with drier years. The correlation between the rainfall and the latitude of the zero line is 0.79, significant at the 99% level. This brief analysis shows that the use of the mean zonal wind as an indication of rain-bringing storms to southern Australia is reasonable in the PD.

The mean winter 10 m zonal wind in the Southern Hemisphere is shown in Figure 5.13 for the PMIP simulations. In all models a southward shift in the zero line can be seen over south west Australia. In all but GEN2 there is also a southward shift over south east Australia. Given the wide range of resolution, model type and parameterisations between the PMIP models, this result is convincing.

The magnitude of the winds is similar across all models also, except MRI2. The winds speeds in MRI2 for both the PD and LGM simulations are unrealistically strong. This is most likely due to the lowest level in the MRI2 model being very high (912 hPa), which is much higher than any other model (Table 4.2). Having the lowest model level so high above the ground would make the translation to 10 m winds less accurate as there is less information in the lower atmosphere.

5.4 Chapter summary and conclusions

The results from the range of circulation diagnostics from the MUGCM, and the consistent response from the PMIP models all point to a modified circulation, particularly for Australia, at the LGM. A circulation that is less conducive to winter rainfall across Australia. Thus the reduction in LGM winter precipitation over Australia is due in part to a shift in the circulation.

In the mean the Walker circulation is depressed, and a weaker Hadley circu-
Figure 5.11: MUGCM Southern Hemisphere 10 m zonal winds for winter in the (a) PD and (b) LGM simulations, and (c) the anomaly. Contour interval: 2 ms$^{-1}$. Differences significant at the 99% level are stippled.
Figure 5.12: Winter rainfall averaged over the south west of Australia (solid curve) overlaid on the latitude of the transition between easterlies and westerlies in NCEP2 10 m winds (dashed curve). Correlation is 0.75
5.4 Chapter summary and conclusions

Figure 5.13: Southern Hemisphere 10 m zonal winds for winter in the PD and LGM PMIP simulations, and their difference. Each sub-figure is clearly labelled with the model, and whether it is PD, LGM or LGM-PD. Contour interval: 2 ms$^{-1}$.
Figure 5.13: Continued...
Figure 5.13: Continued...
Figure 5.13: Continued...
Figure 5.13: Continued...
Figure 5.13: Continued...
Figure 5.13: Continued...
5. Simulated LGM and PD climate: II Winter circulation

Figure 5.13: Continued...

(v) PD, MRI2
(w) LGM, MRI2
(x) LGM-PD, MRI2

Figure 5.13: Continued...
Figure 5.13: Continued...
ulation is seen, with the descending arm placed further south. Hemispheric plots of the zonal wind and the sea-level pressure suggest that much of the southward shift is over Australia and the central Pacific Ocean. Nowhere is there a suggestion of a northward shift in the westerlies as found in the Northern Hemisphere and as might be thought to have happened in response to the extended LGM sea-ice.

The anomalously high winter pressure across Australia at the LGM suggest that there were fewer low pressure systems tracking across southern Australia, while the reduced Eady growth rate shows that the mid-troposphere is more stable, and there is less potential for storms to develop. Identifying and tracking the surface systems directly showed that there were more closed and open low pressure systems tracking across the south of Australia at the LGM, but that they were weaker as they crossed Australia. It is the depth of cyclones, rather than their number that have been shown to correlate well with rainfall across southern Australia (Simmonds et al., 2001).
Chapter 6

Hydrological changes and the moisture budget

6.1 Introduction

The mean changes in the simulated precipitation between the LGM and the PD show that the LGM is drier in the MUGCM and many of the PMIP models. Changes in the large-scale circulation in the MUGCM were shown to contribute to this drying, particularly across southern Australia in winter, with a southward shift in the westerlies and a decrease in the intensity of the storms. A further examination of the changes in measures of the hydrological cycle, and their effects on Australia’s climate and possible signature in proxy evidence is undertaken in this chapter.

Features of the hydrological cycle that will further describe the LGM climate of Australia include the high frequency rainfall variability, shifts in the source region of large scale rainfall and paths to storm events as well as an examination of the hydrological balance at the surface. The variability of the rainfall, including the incidence of extreme events, can modify surface features, such as the fine sediment left by a wetland in the Flinders Ranges that would have been washed away with the intense events in the PD \cite{Williams et al. 2001}. This then forms a proxy that could be compared with the precipitation variability in the model simulations of the PD and LGM. A shift in the water balance between precipitation, runoff and the evaporation from a lake surface has been suggested as the reason behind the existence of high lake levels at the LGM \cite{Galloway 1965} and this will also be explored in the GCM results.
here. The decrease in mean precipitation is explored further by assessing shifts in the atmospheric moisture, shifts in the circulation associated with high rainfall events, and how much the oceans contribute to the moisture in Australia’s precipitation compared to that from the land surface.

### 6.2 Water balance and lake levels

In Chapter 2 the reconstructions of LGM hydrological from a range of proxies were described. A number of studies showed evidence of high lake levels in southeastern Australia at the LGM and their authors suggest that the high levels are not due to increased LGM precipitation, but to decreased potential evaporation. For example: Lake George, near Canberra (Galloway, 1965), Brachina Gorge in South Australia (Cock et al., 1999; Williams et al., 2001), Lake Neekeeya near the Grampians (Bowler, pers. comm. 2002) and Lake Kanyapella in Victoria, (Stone, pers. comm. 2002).

Galloway (1965) determined that the environment around Lake George was cooler and windier at the LGM, but the lake levels were high. He attempted to reconstruct the precipitation and evaporation environment at Lake George by looking to the modern day climate in regions with the same temperature as that reconstructed for Lake George. He deduced that, although the LGM environment was less humid and more windy, which would both contribute to increased potential evaporation, the cooler air would be more like present day winter in a nearby cooler catchment, which has less potential evaporation in the present day. This decrease in potential evaporation would allow the lake level to be high, even though the precipitation was lower.

The water balance of a lake is a combination of the incoming precipitation, runoff and streamflow, the river outflow, evaporation from the lake surface and interactions with groundwater. Changes in the local landscape such as blockages to water flow or river diversions can also have a strong effect on whether a lake exists or not (e.g. Cock et al. (1999)). Lakes with a small catchment and little interaction with groundwater, such as the ‘rain-gauge’ lakes in western Victoria described by Jones et al. (2001), provide a reasonable measure of the balance between precipitation and evaporation. All other lakes will have a strong influence from the amount of run-off and streamflow into them. Bowler (2003) suggested the schematic shown in Figure 6.1 as a way of explaining this difference. The plot shows land from inland arid Australia on the left to the
coast on the right. Two lakes are shown, one close to the point where the values of the annual precipitation totals and the evaporation off the lake are the same. It is assumed that this type of lake has a small catchment, is driven by the balance between precipitation and evaporation, and would have had high water levels at the LGM. The other lake, which has lake evaporation far greater than the precipitation relies on rivers for water, and would have been dry at the LGM.

![Figure 6.1: A schematic of a theory for the moisture balance for two types of lakes, after Bowler (2003). The mountain represents the Great Dividing Range, and the left of the plot is near the centre of Australia. The curves represent annual precipitation and lake evaporation totals. Lakes with limited inflow, due to a small catchment or their position high up in the catchment, respond to the balance of precipitation and lake evaporation, while those with larger catchments, or further downstream, depend on inflow from rivers.](image)

In the current climate, which has a warming trend, there is debate about whether potential evaporation will increase as the climate warms, with GCM output from a number of models suggesting large increases with increasing temperature in simulations of 2030 and 2070 (Pittock, 2003), but recent pan evaporation data showing a consistent decline in many parts of the world (Roderick and Farquhar, 2002, 2004). A part of this decline is linked to an increase in radiation being scattered in the atmosphere before reaching the surface by an increase in atmospheric particulates, for example, volcanic ash (Farquar and Roderick, 2003). In Australia, this decline is believed to be due to local effects - in the northwest there has been an increase in rainfall, which has led to the environmental air being more humid, and thus a reduction in the potential for evaporation from the pan (Nicholls pers. comm. 2004), while in the southeast, the decreasing trend in wind strength reflects the evaporation decreases. Nonetheless, in a cooler climate, if the relative humidity, atmospheric composition and circulation are the same, a decrease in potential evaporation would be
Combining the actual evaporation with the precipitation achieves a budget of water available over land surfaces. Positive values of the mean precipitation minus actual evaporation (P-E) indicate net moisture available for runoff, while a negative balance over land will lead to extensive drying. The long term annual difference (not shown) is very similar in the control and the LGM simulation, with positive values across all of the continent but the south west. There are, however, differences in the seasonal response between the PD and LGM. In summer and spring the PD simulation has more extensive regions of negative P-E (quite dry), while in winter the LGM simulation is drier in the south, in autumn it is drier in the north. The largest change in the P-E balance between the PD and LGM simulation is in autumn.

The balance between the precipitation and the lake evaporation can be explored with the MUGCM. The lake evaporation will be close to the potential evaporation (the amount of evaporation with no restriction on the amount of moisture available at the surface). MUGCM produces the actual evaporation, but does not calculate the potential evaporation. The potential evaporation can be estimated by modifying the actual evaporation equation.

The actual evaporation, E, is defined in the MUGCM following Louis (1979) as outlined in Simmonds (1985):

$$E = \rho C_w \frac{C_D}{D} |u| [q_{sat}(T_s) - q]$$

(6.1)

where $C_D$ is the drag, dependent on the wind speed and the thermal stability $D = 0.74$ from Businger et al. (1971), and $C_w$ is related to how much moisture is available at the land surface, and is dependent on the amount of surface soil moisture, $w_g$. If the soil moisture is 75% or greater of the saturated value, $C_w = 1$, otherwise $C_w = \frac{w_g}{w_{sat}}$. The potential evaporation can be estimated by assuming that the surface was always saturated, i.e. $C_w = 1$. A way to approximate this is to take the mean value of soil moisture in the model output and, if it is less than saturated, multiply the evaporation, $E$, by $\frac{w_{sat}}{w_g}$.

Figure 6.2 shows the precipitation anomalies across Australia for reference, and then the anomalies of evaporation, surface soil moisture, and the reconstructed potential evaporation. It is clear that the precipitation, actual evaporation and soil moisture are closely linked.

The mean annual PD potential evaporation ($E_p$) calculated in this way from
Figure 6.2: Annual LGM minus PD (a) precipitation (mm/day), (b) actual evaporation (mm/day), (c) surface soil moisture (proportion of saturated) and (d) potential evaporation (mm/day). Differences significant at the 99% level are stippled on the precipitation and evaporation plots.
the MUGCM is higher than the estimate calculated from the observations produced by [Chiew et al. (2002)], but the pattern is similar. The anomaly pattern of the potential evaporation (Figure 6.2(d)) shows an increase across much of Australia, indicating that in the MUGCM simulations, with this estimate of potential evaporation, the LGM potential evaporation is higher than at the PD. Australia-wide, P-E_p is consistently negative in both the PD and LGM simulations (not shown), indicating that E_p is always higher than the precipitation, and there is no zero-line across the continent that might suggest regions where there might be high lake levels.

There are many problems in calculating the large-scale pattern of the potential evaporation off a lake. To approach the problem at a more local scale, hydrologists consider greater complexity than the aerodynamic formulation for evaporation (Equation 6.1) shown above. For example, [Linacre (1993)] suggests a simplified version of the Penman equation as an estimate of the evaporation of lakes, and it includes many empirical factors. However, it is assumed that the estimate for lake evaporation arrived at with the MUGCM data is accurate for a comparison between the LGM and PD results, and this method shows an increase in potential evaporation at the LGM. The LGM simulation is also not as cool as some of the proxy evidence suggest, which would alter the degree of potential evaporation.

As an alternative hypothesis, changes to the runoff regime will also alter the lake levels. Some of the high lakes mentioned above will have increased snow cover in their catchments; for example, Lake George. The increased snow would produce a delay in the runoff over winter, and if it is assumed that the potential evaporation is greatest in summer (as shown by [Bowler (1970)]), then this delay in the inflow of winter rain will help maintain the lakes through the warmer months. Vegetation has been shown to be less vigorous due to the reduced atmospheric carbon dioxide levels and cooler temperatures [Berry (2001)]. There was also a shift to increased grassland from forest [Singh et al. (1981) Kershaw (1985)]. Such changes in vegetation would allow less absorption of the surface water by plants, and thus increase the surface runoff. This would help fill lakes high in the catchment, but, if there is a decrease in precipitation, the increased runoff will not add to the levels of lakes fed by rivers further downstream. [Hesse et al. (2004)] also subscribe to the theory of modified runoff as the reason for high lake levels.
6.3 Total atmospheric moisture

Changes in precipitation occur due to two factors - a change in available atmospheric moisture and changes in the mechanism for precipitation. An important field to examine when assessing the hydrologic cycle during such an extreme climate as the LGM, where much of the fresh water is tied up in the Northern Hemisphere ice-sheets, is the total moisture in the atmosphere (precipitable water). The annual average total column moisture is presented in Figure 6.3 for the PD and LGM simulated climates. The strong dependence on latitude and the land-ocean contrast can be seen.

A clearer picture of the changes in the precipitable water is seen in Figure 6.4, which shows the annual difference between the LGM and PD for the MUGCM and the PMIP simulations. The total column moisture is greatly reduced at the LGM in the MUGCM LGM simulation, with only slight increases over the regions of warm CLIMAP SSTs. This shows that a strong contribution to rainfall decreases is the decrease in atmospheric moisture. There are regions of precipitation increase where there is also an annual decrease in precipitable water indicating some change in the circulation to encourage increased precipitation of what little moisture there is.

For most of the PMIP models there is also a strong decrease in the total column moisture. Over regions where the SST has a positive anomaly, such as off the equator in the Pacific, the precipitable water also shows a slight increase in most of the models, but away from those regions there is generally a drier atmosphere. An investigation by Jackson and Stephens (1995) shows that the link between the SSTs and the total column water vapour is strong, particularly in the subtropics, and varies seasonally, with higher water vapour values in summer for the same surface temperatures. In the tropics the link between SSTs and the total column water vapour is less consistent, because regions of strong convection or subsidence can strongly alter the water vapour content over the same SST.

Over Australia, interestingly, although BMRC2 shows a decrease in precipitation at the LGM, the precipitable water in Figure 6.4(b) shows little change, or even a slight increase. This implies that the decrease in precipitation is linked to factors other than the amount of moisture in the atmosphere in the BMRC2 simulations. All other models with results for precipitable water, including GEN2 which has a strong increase in precipitation over Australia, show
6. Hydrological changes and the moisture budget

Figure 6.3: MUGCM annual total column moisture (precipitable water) (mm). for the PD, (a), and (b) for the LGM. Contour interval is 5 mm
Figure 6.4: LGM - PD Annual precipitable water, for all the models. Contours at 2.5 mm, negative contours are dashed and the zero contour is bold. Differences significant at the 99% level are stippled on the MUGCM plot.
Figure 6.4: Continued...
Figure 6.4: Continued...
a decrease in the annual average. Thus, part of the drying evident in many of the models is due to a drier atmosphere.

The warm spot in the CLIMAP SSTs off the east coast of Australia has increased precipitable water and precipitation associated with it. Air masses passing through this particularly moist region before moving over the continent and precipitating might have more moisture available to them than suggested by the long-term mean of the total column precipitable water. This explains in part why many of the positive rainfall anomalies appear to stem from the anomalous hot-spot off the east coast.

The seasonal variation in precipitable water for the climate regions outlined in Chapter 3 is shown in Table 6.1. The greatest reduction is in the northern region, particularly in autumn and summer. The south east shows a similar seasonal pattern.

<table>
<thead>
<tr>
<th></th>
<th>All Aust</th>
<th>Central Aust</th>
<th>N Aust</th>
<th>SE Aust</th>
<th>SW Aust</th>
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<tr>
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<td>-4.1</td>
<td>-7.3</td>
<td>-3.7</td>
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<tr>
<td>djf PD</td>
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<td>-1.2</td>
<td>-4.7</td>
<td>-0.6</td>
<td>-2.1</td>
</tr>
</tbody>
</table>

Table 6.1: PD MUGCM total column moisture over regions of Australia and LGM anomaly. Units: mm

### 6.4 Variability of precipitation

From the range of studies of outlined in Chapter 2 there is limited proxy evidence of the variability of precipitation at the LGM across Australia. The summer monsoon and tropical cyclones bring intense precipitation events in the present day, and if these extend further south, they can leave their signature on watercourses. For example, Brachina Gorge in the Flinders Ranges receives intense rainfall from sporadic monsoonal incursions at present. During the LGM, the gorge did not receive such extreme flows (Cock et al. 1999, Williams et al. 2001), although there was permanent water present. Thus there were no
6.4 Variability of precipitation

rainfall events as intense as can occur from southward monsoonal incursions today. From the north of Australia to the Flinders Ranges there is evidence that the LGM was drier from dune activity on lake beds \citep{Bowler1983, Chen1993, English2001}. To assess the variability of the precipitation, direct model output of 6 hourly precipitation is analysed. Although the temporal variability is high, the broad spatial scale in the model limits the capacity to simulate extreme point values well. A method to ‘downscale’ from the large-scale model output to realistic point rainfall totals, such as the analogue method of \cite{Timbal2004}, cannot be used for past climates. The direct results from the MUGCM will capture the variability of the precipitation within the model, and this is shown, with the understanding that the actual values are for full grid-boxes, rather than a single rain-gauge, and hence the extremes will generally be far lower in the model.

Frequency plots of two years of 6 hourly precipitation amounts are considered at six points around Australia. The location of the six points is shown in Figure \ref{fig6.5}. As it is the changes in the extremes that are being considered the frequency of rain events in the 0 to 10 mm category are not included in the graphs, but shown as a percentage in Table 6.2. The significance of the differences in the distribution of the rainfall events greater than 10 mm was tested using a non-parametric ranked sum test, termed the Wilcoxon or Mann-Whitney test. The higher intensity tails were also tested. The regions considered all have quite different rainfall regimes, and thus the scales on the graphs in Figure \ref{fig6.6} are all different.

Figure 6.5: Location of test on rainfall variability
6. Hydrological changes and the moisture budget

<table>
<thead>
<tr>
<th></th>
<th>Central</th>
<th>NT</th>
<th>QLD</th>
<th>SA</th>
<th>WA</th>
<th>VIC</th>
</tr>
</thead>
<tbody>
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<td>96</td>
<td>91</td>
<td>99</td>
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<tr>
<td>LGM</td>
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<td>98</td>
<td>90</td>
<td>99</td>
<td>98</td>
<td>98</td>
</tr>
</tbody>
</table>

**Table 6.2:** Percentage of 6 hourly periods with zero rainfall for each of the six points on Figure 6.5. The names refer to the State in which the point lies.

In the north of the Northern Territory (NT, Figure 6.6(a)), in an area that gets highly seasonal, monsoonal rainfall, the number of six hourly periods with zero rainfall was 96% for the PD, 98% for the LGM. Figure 6.6(a) shows that the PD has many more low intensity events, and one more extremely high over the 2 years considered. The intermediate amounts are about the same. This indicates that the monsoon was still operating in this LGM simulation, but unseasonal, low volume rainfall events were fewer.

South Australia (SA, Figure 6.6(b)) has much lower rainfall than any of the other regions considered, with the highest number of dry days. In all but the category centred on 40 mm/day the number of rainfall events is higher at the LGM than in the PD. Although these are not particularly extreme events compared to the Northern Territory, there are more LGM extreme events than PD, which seems at odds with the proxy evidence.

In the Central region (Figure 6.6(c)) the majority of the simulated rainfall is from low intensity events. The LGM has fewer of these and more zero rain events. This highlights the increased continentality at the LGM and the decrease in any rainfall from monsoonal incursions. A decrease in rainfall across this region also indicates less interaction between the tropical moisture in the north of the continent and rain-bearing systems in the south.

Near the north east coast (QLD, Figure 6.6(d)), there are some very high intensity events. At the LGM there are more low intensity events, but there are only PD events at the extreme level. The full distribution for the LGM and PD (and the upper tails) are significantly different at the 95% level. In the present day this is an area that would expect the majority of its rainfall from orographically lifted moist westward trade winds, but also some large rainfall events from tropical cyclones making land fall. The high intensity events seen in the MUGCM simulation are from tropical cyclone-like disturbances that exist in the model [Butler 1997]. The lack of any of these high intensity events at the LGM is due to the extended land and fewer tropical cyclone-like disturbances being simulated. This indicates the possibility of a major shift in the rainfall
6.4 Variability of precipitation

Figure 6.6: Frequency of rainfall amounts (mm/day) at points on Figure 6.5 (a) NT, (b) SA, (c) Central, (d) QLD, (e) VIC and (f) SWWA. Events are six hourly over two years. The frequency of zero rainfall is not included. Present day amounts are in light grey, to the left of the value, LGM in darker grey to the right.
Figure 6.6: Continued...
Figure 6.6: Continued...
regime of the north east of Australia at the LGM.

In the south east of Australia (VIC, Figure 6.6(e)) a different change is seen, with a decrease in the number of low intensity events at the LGM, but all the intense events seen are at the LGM. This is most likely due to a shift in the source region, illustrated later in Section 6.5, from the cool waters to the south and west to some events arising from the hot water off the north east coast. This shift in source region to the relatively warm north eastern coastal waters may also be the reason for increased extreme events in the Central and SA regions.

The MUGCM simulates low rainfall for the point in south west Western Australia (WA, Figure 6.6(f)). Between the PD and the LGM there is a shift to lower intensity rainfall, with an increase in events of 10-20 mm/day but no events higher than 40 mm/day, while there are PD events up to 80 mm/day. The distribution in this higher end tail is significantly different for the LGM and PD. This region receives most of its rainfall from fronts embedded in the westerly flow in the present day, with some enhanced rainfall resulting from the front interacting with tropical moisture from the north west. As has already been shown, there was a southward shift in the westerlies and weakening of storms in the LGM simulation, thus a decrease in intense events might be expected.

### 6.5 Air parcel trajectories to precipitation events

As seen in Chapter 4, the precipitation is reduced in all seasons but spring in the MUGCM simulation of the LGM. It was shown that the amount of precipitable water available in the atmosphere is greatly reduced, a likely contributor to the decreased precipitation. As is evidenced from the section on the variability of the precipitation, it is not just the total amount of rainfall that changes, but the structure of the precipitation spectrum. Although the strong reduction in precipitable water might indicate the sole reason for a reduction in precipitation, the reason behind the changes in the variability and spectra will be explained further with an analysis of the shifts in the paths of moisture to high rainfall events.

The top 2% of rainfall events were considered, which vary in their total rainfall amount between the two simulations. The variability in the MUGCM rainfall at the points in northern Northern Territory, eastern Queensland and south west Western Australia (Figures 6.6(a), 6.6(d) and 6.6(f)) show that
6.5 Air parcel trajectories to precipitation events

the top 2% of rainfall events in the PD will have much larger totals than at
the LGM. In contrast there are more extreme rainfall totals at points in South
Australia and Victoria (Figures 6.6(b) and 6.6(e) in the LGM simulation.

Starting from 850 hPa at the time of the high rainfall, the winds from 6
hourly prior output are used to trace back a parcel’s path for four days. The
trajectory scheme was developed at the University of Melbourne, initially by
Rachel Law for movement in two dimensions along a pressure surface (described
in the appendix of [Perrin and Simmonds 1995]), and then extended by David
Noone to three dimensions [Noone and Simmonds 1999]. Integration is done
with a fourth order Runge-Kutta scheme in three dimensions and all interpola-
tions are done cubically.

In the central north of Australia backward trajectories in DJF would be
expected to arise from cross equatorial flow as part of the true monsoon as
described in [Gentilli 1971]. Figure 6.7(a) shows that the majority of the tra-
jectories do indeed come from the north, with some input from the direction of
the tradewinds. With the Gulf of Carpentaria being land at the LGM it might
be expected that the path of these trajectories would change. In the LGM (Fig-
ure 6.7(b)) there appears to be two distinct paths - one from the north west,
and the more preferred one from the east. There are indeed fewer trajectories
that cross the Gulf of Carpentaria.

In the south west of Western Australia it is observed that rainfall is from
fronts embedded in the westerlies. High winter rainfall totals along the west
cost are associated with the pre-frontal air mass, and the timing of beginning
the trajectory relative to the passage of the front will determine to some extent
the path of the parcel (not shown). Thus it would be expected that both the
path from the pre-frontal moisture source and the front in the westerlies would
be captured. In the PD simulation shown in Figure 6.8 both these directions
can be seen, indicating conditions close to observed. The LGM simulation shows
far fewer trajectories in the westerlies, indicating a shift in the circulation.

The trajectories to high rainfall events in the south east are predominantly
zonal in the PD, streaming in from the west (Figure 6.9). The LGM simulation
has trajectories arising from many different locations, even Antarctica. The
majority of them pass over the ‘hot spot’ off Australia’s east coast. This is
obviously an excellent source of moisture for this region. The track of the
trajectories is very interesting though - in the current observed climate it is
unlikely that so many parcels of air that pass through that warm spot would
Hydrological changes and the moisture budget

Figure 6.7: Summer MUGCM trajectories to high rainfall events in the monsoon region. (a) PD and (b) LGM

The changes in the trajectories to high rainfall events are clear. The land bridge to the north of Australia limits the path of moist air from the north in the summer monsoon. In the southwest many of the trajectories to high rainfall events in the PD are from the west, while there are also many linked with moisture from more tropical latitudes. At the LGM the majority of trajectories are from the north west, with few trajectories from the west. This change reflects the southward shift in the large scale circulation explored in Chapter 5.

In the south east, where there are extreme rainfall events with totals higher than at PD in the LGM simulation, the shift from high rainfall being associated with trajectories in the westerlies to trajectories from more tropical latitudes is even more marked. With an anomalous region of warm SSTs off the east coast, and the majority of trajectories to high rainfall events passing through it, it is no surprise that the extreme totals are higher in the LGM simulation as the moisture comes from a closer, warmer, probably moister, source. The
same reasoning would apply to the high LGM extremes in southern Australia. Proxy evidence suggest that the lake at Brachina Gorge (or wetland) was not disturbed by monsoonal incursions at the LGM (Cock et al., 1999; Williams et al., 2001). The analysis of the LGM model results here suggest that the high totals are indeed not from monsoonal incursions, but from air laden with moisture brought in from the warm SSTs to the east.

6.6 Recycling of continental moisture

The proportion of moisture in the air that is from the local land surface gives an indication of the strength of the link between the atmosphere and the land, as well as an indication of the degree to which the surrounding oceans affect the continental hydrology. Understanding how strong the interaction between the surface and subsequent rainfall is will allow us to gauge how our large-scale activities at the surface are affecting the climate. A key concept in understanding this is associated with the concept of moisture recycling. The moisture recycling
Figure 6.9: Winter MUGCM trajectories to high rainfall events in southern Victoria. (a) PD and (b) LGM

is the amount of evaporation arising from a region and then returning to the same region as precipitation.

In this section the influence of the surface on subsequent moisture levels in the atmosphere and rainfall around Australia will be assessed using two methods with output from the MUGCM for the PD and LGM simulations. Changes in the degree or seasonality of the moisture recycling will give an appreciation for the shifts in influence between the local land surface evaporation and maritime air on Australia’s rainfall.

6.6.1 Calculation of the recycling ratio from the large-scale atmospheric moisture balance

Budyko (1974) presents an approximation to the equations of water exchange. The water exchange model is based on a breakdown of the moisture for precipitation ($P$) over a region coming from two sources, one ‘local’ from within the region, via evaporation ($P_m$), and the other brought from outside the region by
advection ($P_a$): $P = P_m + P_a$. The moisture recycling ratio is the ratio of the precipitation derived from local sources to the total: $\frac{P_m}{P}$. A schematic of this conceptual model is shown in Figure 6.10. In Budyko’s model movement across the region is considered as a one dimensional stream-tube. The model has been the basis for many subsequent studies, such as that of Trenberth (1999), who used a similar method to explore the influence of the length of the region on the amount of moisture recycling. The Budyko model and other one dimensional models are reviewed and re-visited by Burde and Zangvil (2001a). Brubaker et al. (1993) extended the one dimensional model to two dimensions, and it is this method that will be used and modified to examine irregularly shaped regions across Australia.

There have been a number of methods that have followed different paths in their development than that presented in Budyko (1974). Eltahir and Bras (1994) also partitioned the water vapour fluxes, but applied their method in an iterative fashion, enabling a spatial pattern of the moisture recycling to emerge. Savenije (1995, 1996) explore a number of indicators of the moisture recycling in the Sahel, including the salinity of the rainfall, the amount of runoff and the distance inland from the sea. Joussaume and Sadourny (1986), Koster et al. (1986) and Koster and Suarez (1995) explore the source region of precipitation over continents using tracers in a GCM. This method will be explored further in the next section.

For techniques for estimating the moisture recycling ratio following Budyko (1974), the area of the region considered will have a large impact on the value of the recycling. For the whole globe, all moisture comes from within the ‘region’, and the moisture recycling ratio is 1.0, while for an extremely small area, no local evaporation contributes to the precipitation, and the moisture recycling ratio is 0.0. From the equation for the recycling ratio used by Eltahir and Bras (1996), they suggest that if the supply of advected moisture is large, then the recycling ratio is linearly related to the area, whereas for regions where the evaporation is much more important, the recycling ratio is less dependent on the size of the region. This is illustrated well in Figure 5 of Trenberth (1999).

**Method**

The method of Brubaker et al. (1993) will be used, with some extension to irregularly shaped regions. The steps in the development of the final equation are outlined below, along with the assumptions made.
Figure 6.10: Conceptual model of the atmospheric moisture fluxes over a land region, from Brubaker et al. (1993). $E$ is evaporation, $P$ is the total precipitation, $F^+$ is the inward flux of moisture and $F^-$ the outward, $P_m$ is the precipitation derived from local sources, while $P_a$ is precipitation from remote. $W$ is atmospheric moisture storage.

The atmospheric moisture balance is

$$\frac{1}{g} \nabla \cdot \int_0^P qv \, dp + \frac{\partial W}{\partial t} = E - P \quad (6.2)$$

where $q$ is the specific humidity, $E$ is the actual evaporation, and $W$ is the storage term in Figure 6.10. Over a period of time much longer than the mean moisture residence time in the atmosphere of 8 days (Trenberth, 1998), the term $\frac{\partial W}{\partial t}$ becomes small compared with the other terms and can be neglected. The divergence of the total column moisture flux could be expressed approximately as

$$\frac{1}{g} \nabla \cdot \int_0^P qv \, dp \approx F^- - F^+$$

where $F^+ = \sum \frac{1}{g} \int_{P_m}^0 qv \, dp \mid L^+$, the flux of total column moisture into the region, which will be of remote origin, ($L^+$ is the length of all inward boundaries, and $v = v\hat{n}$), while $F^- = \sum \frac{1}{g} \int_{P_a}^0 qv \, dp \mid L^-$ is the moisture flux across any outgoing boundary, which will be the remaining moisture of both local and remote origin after precipitation ($L^-$ is the length of all outward boundaries). The outgoing moisture ($F^-$) can be expressed as the sum of the residual remotely
6.6 Recycling of continental moisture

derived moisture, in terms of $F^+$, and the locally derived residual:

$$F^- = (F^+ - P_aA) + (E - P_m)A$$

where A is the area of the region.

An assumption is made that the atmosphere is well mixed, and the proportion of rainfall from local and remote sources corresponds to the proportion of locally and remotely derived moisture in the air:

$$\frac{P_m}{P_a} = \frac{Q_m}{Q_a}$$

A further assumption is made that the moisture concentrations change linearly along the traverse through the region, and thus the local or remote moisture components are the mean of the incoming and outgoing local or remote moisture. The average moisture derived from local sources ($Q_m$) is the mean of the incoming local moisture (=0) and the local part of $F^-:

$$Q_m = \frac{0 + (E - P_m)A}{2}$$

The remotely derived moisture ($Q_a$) is the mean of the incoming remote moisture ($F^+$) and the non-local component of $F^-:

$$Q_a = \frac{F^+ + (F^+ - P_aA)}{2}$$

$$= F^+ - \frac{P_aA}{2}$$
With values for \( Q_m \) and \( Q_a \), and the assumption of a well-mixed atmosphere, the recycling ratio \( \left( \frac{P_m}{P_a} \right) \) can be calculated through a number of steps:

\[
\frac{P}{P_a} = Q_m + 1 = \frac{EA - P_m A}{2F^+ - P_a A} + 1 = \frac{EA - PA + P_a A}{2F^+ - P_a A} + 1
\]

\[
\frac{P}{P_a} - 1 = \frac{EA - PA + P_a A}{2F^+ - P_a A}
\]

\[
\frac{2F^+ P}{P_a} - PA - 2F^+ + P_a A = EA - PA + P_a A
\]

\[
\frac{2F^+ P}{P_a} = EA + 2F^+
\]

\[
\frac{P}{P_a} = \frac{EA}{2F^+} + 1
\]

We know that:

\[
\frac{P_m}{P} = 1 - \left( \frac{P}{P_a} \right)^{-1}
\]

which leads to the equation for the recycling ratio used by Brubaker et al. (1993):

\[
\frac{P_m}{P} = \frac{1}{1 + \frac{2F^+}{AE}}
\]

(6.3)

Brubaker et al. (1993) used this formula for rectangular areas, assuming one boundary the inward and the opposite the outward. This has been extended in this thesis so that each boundary segment is considered, the flux across it calculated, and added to \( F^+ \) if the direction of transport is into the region. A new step was also added to the MUGCM to help with these calculations. In calculating the total column moisture flux, the moisture must be multiplied by the wind at very fine temporal resolution to capture the full covariances, rather than just using the mean values of moisture and wind. This could be done off-line, with 6 hourly output, but for ease, an extra analysis step was put into the MUGCM to multiply the moisture and each component of the wind at each time-step, and write out the monthly averages as new fields.

Burd and Zangvil (2001a) note that the approximation made by Brubaker et al. (1993) that the average horizontal flux of moisture over the region is the arithmetic mean of the incoming and outgoing moisture can lead to an
underestimation of the recycling ratio. If the flow is not parallel the recycling ratio will be less than the actual value, decreasing with the increasing complexity of the flow \cite{BurdeZangvil2001}. Although here the influx of moisture is calculated at all edges of the region, and it may thus be any shape, the assumptions of \cite{BrubakerEtal1993} leading to Equation 6.3 still hold. \cite{BurdeZangvil2001} describe a model that overcomes this limitation, but it has some short-comings in its estimation of moisture input and its application to data is not straight-forward. The streamlines for total column moisture over Australia (not shown), show a reasonably smooth flow from west to east in winter and spring across each of the regions, thus the values derived using the method of \cite{BrubakerEtal1993} can be treated with some confidence in those seasons. There are more complicated flows in summer and autumn and thus the recycling ratio may be underestimated in those seasons.

Results and discussion

The moisture recycling ratio as outlined above was calculated for Australia as a whole and also for the five climate regions shown in Figure 3.15. The area of each region is important to the final moisture recycling value, as outlined above, and is shown in Table 6.3. The south west and southern south east (SE2) regions might be expected to have low recycling simply because their area is relatively small.

<table>
<thead>
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<td>1.0</td>
<td>0.9</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 6.3: Area of the climate regions in Figure 3.15 in units of $\times 10^6$ km$^2$

The moisture recycling ratio for all of the present-day land extent of the Australian continent and each of the climate regions are shown in Table 6.5 for the PD and LGM simulations. The ratio is reasonably low, particularly in the southern climate regions (SE2 and SW) in both the PD and LGM simulations.

To put the values found over Australia into context, other regions were considered. Two other regions were chosen for a PD simulation - the Amazon and the Sahel (Table 6.4). These regions were chosen due to their very different moisture regimes in the present day. The Amazon is largely wet rainforest while the Sahel is desert. The recycling ratio over each of these regions in the MUGCM is:
Both the Amazon and Sahel have moisture recycling values of the same magnitude, with the same seasonality (the Sahel is in the Northern Hemisphere) as over Australia. To compare these values with those from Australia the dependence of recycling on the area considered must be appreciated. Australia’s area is $7.8 \times 10^6$ km$^2$, the Amazon’s is $6.4 \times 10^6$ km$^2$, and the Sahel’s area is only $3.7 \times 10^6$ km$^2$. From the equation for calculating the moisture recycling ratio with averages, Equation 6.3, the dependence on area can be determined. If evaporation and $F^+$ are constant, the moisture recycling ratio will increase as the area increases, however the rate of increase is dependent on the actual values of $E$ and $F^+$. This is illustrated in Figure 6.14, which shows values of the recycling ratio for different areas given three evaporation and three $F^+$ values. When advection is low (A, D, and G), and the recycling ratio is high, it responds strongly to changes in area. At lower recycling values, the dependence is less strong. For a recycling value of about 0.15 over an area $7.8 \times 10^6$ km$^2$, the recycling for $6.4 \times 10^6$ km$^2$ would be about 20% less (0.13), and for $3.7 \times 10^6$ km$^2$ about 45% less (0.08). Thus the Sahel has surprisingly strong recycling, and Australia has relatively low recycling.

To gain an appreciation of the contribution from the mean regional evaporation and the moisture flux, the evaporation in each region for the PD and LGM is shown in Table 6.6, and the value of $F^+/A$ in Table 6.7.

Table 6.6 shows the PD simulated evaporation and the LGM anomaly. There is a decrease in the amount of LGM evaporation compared to that in the PD in all seasons and regions except spring in the central, south east and south west. To assess the cause of the increased LGM evaporation in spring the influence of each of the components (Equation 6.1) is considered. The temperature modifies the evaporation through both the corresponding saturation mixing ratio and the stability of the lowest layer. The wind and dryness of the air are also strong factors in the amount of evaporation. There is a decrease in precipitable water across Australia, with the greatest decrease in autumn, followed by summer, winter, and least in spring. Thus the air in the LGM springtime simulation is
6.6 Recycling of continental moisture

cool and relatively moist, both of which might contribute to a decrease in the amount of evaporation. The mean winds in the LGM simulation for winter and spring are stronger than the PD except in the south east, while in summer there is a decrease. In autumn there is no change. Thus the increased wind strength does not allow for as large a decrease in the spring LGM evaporation as in other seasons, even though the air is moist.

In the south, much of the rainfall is from fronts in large-scale weather systems, thus there would be strong advection into the region. This can particularly be seen in SE2, the south eastern region including Tasmania, that has the highest moisture influx compared to all other regions in every season (see Table 6.7). The influx into this region is reduced at the LGM, possibly linked to the southward shift in the westerlies, but it is still larger than any other region. The evaporation in the south eastern region is also high in winter and spring, due to the wet winter conditions (see Figure 3.9), but this is offset by the large moisture influx, so the moisture recycling ratio is low.

The north region has a relatively high moisture recycling ratio in summer in the PD, linked to high summer evaporation, while the other seasons have both less evaporation and lower recycling ratios. Both the evaporation and moisture influx decrease in all seasons into the LGM in the north region, and there is no change in the recycling ratio value in summer, but an increase in autumn. Thus the land surface becomes a stronger influence on autumn rainfall in the north at the LGM.

The eastern region (SE1) has a reasonably vigorous hydro-climate, with strong evaporation in all seasons and high moisture inflow in summer and spring. In autumn it has the highest moisture recycling value, associated with higher autumn evaporation than any region and low moisture influx. This reflects a weakness of the link to climate influences external to the region, which might be linked to the predictability barrier for El Niño. This result is worthy of further consideration for improving seasonal forecasts over this season, and has been explored with data in Hope et al. (2002). The LGM moisture inflow into this region is less than the PD in every season, while the evaporation decreases in autumn, but stays the same or increases in the other seasons. This leads to increases in the recycling, which is strong in all seasons at the LGM. The warm ocean anomaly off the east coast leads to anomalously increased precipitation in this region, particularly in winter, and this is reflected by the high evaporation at this time.
6. Hydrological changes and the moisture budget

The central region has the least moisture inflow of any region (Table 6.7), as would be expected given its continental nature. This continentality is heightened at the LGM, and this is shown by a further decrease in the moisture influx. The central region is also the driest, and the evaporation is correspondingly low. Of the little moisture it has, it has reasonably high moisture recycling in summer and autumn in the PD and the highest recycling in summer at the LGM. These values are large in part due to the large area of the central region. The moisture recycling values for the all-Australia average follow the seasonality of the changes in the central region.

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<tr>
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<td>DJF PD</td>
<td>0.12</td>
<td>0.13</td>
<td>0.11</td>
<td>0.08</td>
<td>0.04</td>
<td>0.02</td>
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<td>0.03</td>
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<td>0.12</td>
<td>0.18</td>
<td>0.04</td>
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<td>0.04</td>
<td>0.04</td>
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<td>0.21</td>
<td>0.05</td>
<td>0.04</td>
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<tr>
<td>SON PD</td>
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<td>0.03</td>
<td>0.13</td>
<td>0.09</td>
<td>0.03</td>
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Table 6.5: Moisture recycling ratio calculated from data averages from the PD and LGM MUGCM simulation for all Australia and each climate region

<table>
<thead>
<tr>
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<td>2.36</td>
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<tr>
<td>DJF dif</td>
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<td>0.09</td>
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<td>0.22</td>
<td>-0.10</td>
<td>0.83</td>
<td>-0.19</td>
<td>0.16</td>
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</table>

Table 6.6: PD MUGCM evaporation over regions of Australia and LGM anomaly, mm day$^{-1}$

These results highlight that precipitation over Australia is largely driven by moisture advected onto the continent. There is some recycling of that precipitation, particularly in summer in the north and autumn in the east. At the LGM the atmospheric hydrological cycle over Australia is in general less vigorous, with less moisture inflow in every season and region, and a reduction in evaporation in most seasons, except in regions where there is a precipitation increase.
6.6 Recycling of continental moisture

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<th>Aust</th>
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</tr>
<tr>
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<td>3.9</td>
<td>12.0</td>
<td>6.4</td>
<td>18.1</td>
<td>10.3</td>
</tr>
<tr>
<td>MAM dif</td>
<td>-0.7</td>
<td>-0.7</td>
<td>-2.0</td>
<td>-2.1</td>
<td>-3.6</td>
<td>2.9</td>
</tr>
<tr>
<td>JJA PD</td>
<td>7.2</td>
<td>6.1</td>
<td>13.8</td>
<td>10.5</td>
<td>25.0</td>
<td>13.8</td>
</tr>
<tr>
<td>JJA dif</td>
<td>-1.8</td>
<td>-2.6</td>
<td>-2.0</td>
<td>-7.0</td>
<td>-9.9</td>
<td>-3.6</td>
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<tr>
<td>SON PD</td>
<td>6.9</td>
<td>5.2</td>
<td>12.4</td>
<td>14.8</td>
<td>27.2</td>
<td>9.4</td>
</tr>
<tr>
<td>SON dif</td>
<td>-1.2</td>
<td>-1.0</td>
<td>-1.4</td>
<td>-7.1</td>
<td>-7.9</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Table 6.7: PD MUGCM \((J^+/A)\) for regions of Australia and LGM anomaly, \(\text{mm day}^{-1}\)

due to the anomalously warm SSTs off the east coast, such as the eastern region in spring.

6.6.2 Estimation of the moisture recycling with a tracer in the MUGCM

The method used to calculate the recycling here has limitations due to the assumptions made. Brubaker et al. (2001) suggest using a trajectory analysis that includes a moisture balance calculation at every step to determine the evaporative source of precipitation as an improved method over the one used here. This would be an interesting study for the Australian region, however it is beyond the scope of this thesis. Another method to calculate the recycling ratio directly is by tracing moisture in a GCM. This is described here.

Joussaume and Sadourny (1986), Koster et al. (1986), Koster and Suarez (1995), Numaguti (1999), Noone (2001) and Hope et al. (2002) all included a tracer of moisture into a GCM, with the tracer’s source only from evaporation in pre-set regions. They used the method to investigate the source (and/or recycling) of moisture for precipitation over certain places. Thus the recycling ratio can be calculated directly using a GCM. Moisture entering the atmosphere from a specified area is ‘tagged’ and then the water in precipitation can be divided into that arising from the ‘tagged’ source or from elsewhere. The moisture recycling ratio can then be calculated from its direct definition: \(\frac{P_m}{P}\).
Method

As was done in the studies above, the moisture variable, and all its processes was duplicated entirely with a second variable containing moisture evaporating only from a specified source region. Moisture is treated as a spectral field in this version of the MUGCM, and one problem for the moisture field in general is that values sometimes become negative. This problem is overcome by bringing negative values up to zero at each time step, and removing this water from the zonal average. Numaguti (1999) use a similar method in their model, but found that it created problems in the tracer field. To overcome this, and for completeness, a second tracer was applied, with moisture arising from all points outside the source region. These two values were then summed and brought into line with the full moisture field at each time step.

Results and discussion

The area weighted values of $\frac{\Delta P}{P}$ found using a tracer in the MUGCM for PD and LGM simulations over all of Australia are shown in Table 6.8. The ratios for all Australia are larger than those calculated from the large-scale atmospheric moisture budget. This perhaps reflects the problem of the assumption of straight flow across the region highlighted by Burde and Zangvil (2001a,b), which would reduce the recycling ratio calculated from data averages. In the PD results for all Australia the seasonality has changed, with the results from the moisture budget having spring with the least recycling (0.06), while the direct results from the GCM suggest the least recycling occurs in winter (0.113). Both methods show that there is the highest recycling in summer. There is a reduction in the all-Australia recycling ratio calculated using a tracer at the LGM compared to the PD in all seasons, unlike when the ratio is calculated with averages. The flow is more complex in the PD than at the LGM (Figure 5.1), thus the PD all-Australia recycling value might be less than expected, adding credence to the suggestion that complex flow will lower the recycling ratio calculated with the equation of Brubaker et al. (1993), as suggested by Burde and Zangvil (2001b). The mean flow in the LGM simulation has easterlies extending over much of the continent, with little interaction with the ‘true’ monsoon from the north, leading to a less complex flow than that in the PD, thus the PD recycling ratio calculated using averages in the previous section might be lower than the actual value.
### 6.6 Recycling of continental moisture

<table>
<thead>
<tr>
<th></th>
<th>Aust</th>
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<td>0.064</td>
<td>0.069</td>
<td>0.042</td>
<td>0.040</td>
<td>0.012</td>
</tr>
<tr>
<td>DJF LGM</td>
<td>0.153</td>
<td>0.063</td>
<td>0.072</td>
<td>0.051</td>
<td>0.026</td>
<td>0.013</td>
</tr>
<tr>
<td>MAM PD</td>
<td>0.161</td>
<td>0.074</td>
<td>0.064</td>
<td>0.042</td>
<td>0.036</td>
<td>0.021</td>
</tr>
<tr>
<td>MAM LGM</td>
<td>0.122</td>
<td>0.055</td>
<td>0.067</td>
<td>0.046</td>
<td>0.029</td>
<td>0.015</td>
</tr>
<tr>
<td>JJA PD</td>
<td>0.113</td>
<td>0.056</td>
<td>0.033</td>
<td>0.044</td>
<td>0.036</td>
<td>0.030</td>
</tr>
<tr>
<td>JJA LGM</td>
<td>0.090</td>
<td>0.047</td>
<td>0.017</td>
<td>0.034</td>
<td>0.034</td>
<td>0.031</td>
</tr>
<tr>
<td>SON PD</td>
<td>0.151</td>
<td>0.053</td>
<td>0.037</td>
<td>0.039</td>
<td>0.043</td>
<td>0.024</td>
</tr>
<tr>
<td>SON LGM</td>
<td>0.124</td>
<td>0.064</td>
<td>0.027</td>
<td>0.049</td>
<td>0.044</td>
<td>0.031</td>
</tr>
</tbody>
</table>

**Table 6.8:** PD and LGM Moisture recycling ratio ($P/P$) for Australia from a tracer in the MUGCM for all Australia and each climate region

The results for the climate regions (Table 6.8) are reasonably low for all regions and seasons. The LGM results are not that different from the PD, with smaller LGM values in the southern regions in summer and autumn and smaller values in the north and central in winter. In the seasons with higher recycling ratios when calculated using averages, the values are are much smaller when calculated with the tracer (e.g. 0.16 compared with 0.042). There are no instances of a recycling ratio greater than 0.1 in any of the regions calculated with a tracer. There appears to be a greater dependence on area than when the ratio is calculated from the data averages. Figure 6.11 shows the area of each region and its average annual recycling ratio on different scales, highlighting the strong drop in recycling with a change in area. To illustrate that this relationship is not so strong with the recycling ratio is calculated with the averages, the PD values of these are also included in Figure 6.11.

The seasonality of the moisture recycling in the climate regions when using the two methods has some differences. In the PD, the seasons when moisture recycling (calculated from averages) is dominant are summer in the north (0.11) and autumn in the SE1 region (0.16). When the recycling is calculated with a tracer in the model, although the magnitudes are smaller as outlined above, the relative difference between summer and winter is less. The recycling in the north in summer (0.069) and SE1 in autumn (0.042) is relatively strong, but there is also strong recycling in autumn in the north (0.074) and both summer (0.042) and winter (0.044) in the SE1 region. If the method using the tracer eliminates the limitations due to the changing complexity of the flow with the seasons, this may indicate that the striking seasonality seen when the recycling is calculated with averages says more about the flow regime in that season than
the hydrological signature. The LGM simulation shows more similarity in the seasonal response between the two methods, perhaps due to the simpler flow structure compared to the PD.

**Figure 6.11:** Relationship between the area over which the moisture recycling ratio is calculated with a tracer in the MUGCM and the value of the average recycling ratio, for the PD simulation. The recycling ratio calculated from averages is also included.

By using the MUGCM the spatial variability of the rainfall arising from the Australian continent can be plotted. Figure 6.12 shows the maps of PD $\frac{P}{P}$, which show local moisture shifting off-shore to the south east. The maps of the spatial extent of precipitation from moisture arising from the Australian continent in the LGM simulation are shown in Figure 6.13. The amount of recycled moisture in the rainfall on the continent is greatly decreased compared to the PD and moisture arising from the continent does not precipitate far from the shores.

There is a reduction in the moisture recycling in most seasons and regions in the LGM simulation, compared to the PD. This indicates that although there was an increase in the continentality of Australia due to the lowered sea-level, the influence from the land surface on the subsequent rainfall is diminished. This would lead to an even stronger influence on the climate of Australia from incoming fluxes of maritime air.
Figure 6.12: MUGCM PD recycling ratio for Australia using a tracer. (a) DJF, (b) MAM, (c) JJA and (d) SON
Figure 6.13: MUGCM LGM recycling ratio for Australia using a tracer. (a) DJF, (b) MAM, (c) JJA and (d) SON
6.6 Recycling of continental moisture

Figure 6.14: The moisture recycling ratio’s dependence on area, calculated with Brubaker et al. (1993)’s equation for different values of evaporation and $F^+$. A, B, and C have the evaporation set to 1.0 mm day$^{-1}$, while $F^+$ is 5, 25 and 45 kg×10$^{12}$day$^{-1}$ respectively. D, E, and F have the same values of $F^+$, with evaporation set to 2 mm day$^{-1}$, and G, H, and I have evaporation set to 3 mm day$^{-1}$.
6. Hydrological changes and the moisture budget

6.7 Chapter summary and conclusions

The precipitable water is greatly reduced in GCM simulations of the LGM, compared to the PD, except near regions of increased SSTs, and in the BMRC simulation. The reduction in precipitable water is due to the lower global temperatures simulated.

Australia has relatively low moisture recycling ratios in all seasons compared to other regions around the globe, indicating that Australia’s rainfall is strongly influenced by the surrounding oceans. The Australia-wide recycling values are lower in the LGM simulation in all seasons when calculated directly from the modelled ‘local’ and total precipitation. This is not the case when the recycling is calculated using the method of Brubaker et al. (1993), although there may be limitations from the assumptions made in this method. However, in assessing the components that make up Brubaker’s equation it can be seen that it is in general both the local evaporation and the amount of moisture advected over the continent that decrease in the LGM simulation, highlighting a strong decrease in the strength of the hydrological cycle.

There is an increase in the potential evaporation across much of Australia at the LGM compared to the PD. This is at odds with the high lake levels at some non-arid sites in Australia’s south east being explained by low potential (or lake) evaporation. Given the stresses on the vegetation from lower atmospheric carbon dioxide and temperature, and a shift to grasses from trees seen in pollen evidence from around Lake Carpentaria (Torgersen et al. 1988) to around Lake George Singh (1983), the vegetation would not have utilised as much water at the LGM as in the PD, and thus runoff for a short distance would increase, even if the precipitation declined. Precipitation falling as snow will not flow immediately into lakes, but the runoff will occur in spring, and perhaps even into early summer, thus providing water to the lakes as the temperatures warm and evaporation increases. These results suggest that the lakes that were full at the LGM are responding to increases in the surface runoff and snowmelt, rather than reflecting the P-E\_P balance. In more arid locations proxy evidence shows dry lakes, which were simply linked to the lowered precipitation levels at the LGM.

The simulated rainfall variability at the South Australian point does not match the proxy reconstructions. In the south there is the added contribution of rainfall from different source regions. The results near the north east coast
are very interesting, indicating a strong decrease in the number of tropical cyclone-like disturbances in this LGM simulation.
6. Hydrological changes and the moisture budget
Chapter 7

Sensitivity to LGM boundary conditions

7.1 Introduction

The simulation of the LGM is reasonably consistent across the GCMs surveyed earlier, but in some cases the results do not match the proxy evidence across Australia. The aim of this chapter is to investigate what aspect of the LGM boundary conditions lead to the cooling, drying and southward shift in the westerlies seen in the LGM simulation. To do this, the boundary conditions suggested by PMIP are applied individually into the MUGCM PD simulation to determine the influence they each have on Australia’s temperature, precipitation and circulation. The boundary conditions tested include the changes in the incoming solar radiation, the decrease in atmospheric carbon dioxide, the change in the sea surface temperatures, the expansion of sea-ice, and the drop in sea-level, coupled with the ice-sheets in the Northern Hemisphere. The boundary conditions that lead to the largest change will then be altered following suggestions in the literature and re-applied to determine if a climate more in line with the proxy evidence could be simulated with the altered boundary conditions.

7.2 Temperature

The reduction in temperature across Australia in the LGM simulation is not as extreme as the suggested reductions from some proxy evidence. The glacial
evidence in the south east suggests a cooling of between 6 and 10°C ([Bowler et al., 1976] [Colhoun, 1983]) while the temperature reconstructions from egg shells in central Australia ([Miller et al., 1997]) indicate a temperature depression of at least 9°C. The MUGCM Australia-wide (PD land extent) annual mean temperature reduction of 2.06°C is much less than this.

To capture the changes in air temperature without the extreme changes noted previously from the replacement of one surface type with another, for example land being revealed as the sea-level is lowered, the temperature at the lowest sigma level will be considered rather than the 2 m temperatures.

**Figure 7.1:** MUGCM anomaly of annual near surface air temperature. PD boundary conditions with LGM SST minus the PD. Contour interval: 1°C

**Figure 7.2:** MUGCM anomaly of annual near surface air temperature. PD conditions with LGM solar input minus the PD. Contour interval: 0.1°C
The annual difference between the PD simulation and PD simulations with each LGM boundary conditions applied individually, are presented in Figures 7.1 to 7.5. The Australia-wide annual average anomalies are shown in Table 7.1, note that the differences will be slightly different from those calculated for the full PMIP simulation with the temperature at 2 m. The boundary conditions that produce major global changes in the temperature are the modified SSTs, sea-ice extent and ice-sheets. The extensive ice-sheets on the continents in the Northern Hemisphere are teamed with the sea-level drop to account for the new land exposed and covered in ice. The other boundary conditions produce minimal but potentially important change.

With the CLIMAP SSTs imposed in the PD simulation, the temperature reductions are nearly global, with slight warming over the north and south east Pacific Ocean, as shown in Figure 7.1. The cooling is reasonably consistent over both ocean and land. Off the north east coast of Australia the hot spot from the SSTs is evident, but across the continent there is cooling, with anomalies of about 1.5°C. The Australia-wide annual average anomaly is -1.66°C, greater than with the full LGM boundary conditions.

The changes in solar input between the LGM and the PD are minimal, and, once input into the MUGCM, produce no differences in simulated temperature greater than 1°C. Figure 7.2 shows cooling at high latitudes, which might be expected from the slightly decreased obliquity, which would decrease the summer insolation at high latitudes.
The decrease in atmospheric carbon dioxide concentration leads to a slight cooling almost everywhere (Figure 7.3). As with the solar changes this is by no more than 1°C. The majority of the cooling is over land, as the heat-loss as longwave radiation from the land at night is allowed to escape due to the lowered greenhouse gas concentration. In Australia there is a region of warming in the north. This warming is not evident at the surface where the temperature is cooler over all of Australia. The cooling seen at the lowest sigma level extends right through the troposphere, though in the northern summer high latitudes there is some warming.

The LGM ice sheets on the Northern Hemisphere continents, the sea-level drop and the associated exposure of land would be expected to produce a range of responses. These boundary conditions are imposed together in the PD simulation. The annual anomaly from PD is shown in Figure 7.4. On all continents except south-east Asia and parts of Australia there is significant cooling. This would be expected in the location of the new ice sheets. The slightly higher orography would also produce a cooling effect. For the increase of 120 m, given the standard atmosphere, the cooling would range from about 1.0 to 1.5°C, depending on the moisture content of the air. At the surface the distinction between cooling over land and no change over ocean is very clear. In the zonal average, the surface anomaly is one of cooling everywhere, but the vertical profile quickly switches to warming at most latitudes up to about 800 hPa from where there is cooling aloft.
Figure 7.5: MUGCM anomaly of annual near surface air temperature. PD boundary conditions with LGM sea-ice extent minus the PD. Contour interval: 1°C

Figure 7.5 shows the changes in the first sigma level temperature between the control and the simulation including the extended sea-ice from the CLIMAP reconstruction. The inclusion of the LGM sea-ice in the PD simulation produces strong cooling in the high and mid latitudes, with little change in the tropics and subtropics. The south of Australia is cooled by up to 2°C, but there is slight warming through the north west.

The simulations with decreased atmospheric carbon dioxide content or increased topography cause a clear cooling over land at the surface but at the lowest sigma level there is already a slight warming over north Australia. The boundary condition that leads to the strongest temperature reductions across Australia are the CLIMAP SSTs.

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Table 7.1: Annual near surface air temperature over different regions. Control total, and differences from control, °C

Earlier it was seen that the LGM simulation produced an increase in the seasonality over Australia, with cooler winters and less cool summers than in
164

7. Sensitivity to LGM boundary conditions

<table>
<thead>
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Table 7.2: as Table 7.1 but for JJA

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Table 7.3: as Table 7.1 but for DJF

To help understand how each of the individual LGM boundary conditions influence the seasonality shift, Table 7.2 shows the temperature averaged over each climate region for winter (JJA) and Table 7.3 for summer (DJF). The bold numbers indicate that the difference is significant at the 95% level. The significance level is calculated using the method of Chervin and Schneider (1976), based on the Student t-test.

The changes from control to CLIMAP SSTs result in an increase in seasonality across all regions of Australia. There are reductions in temperature right across the continent, with the cooling in winter in central and north Australia greater than that with the full PMIP boundary conditions. In summer all regions except the north are cooled by more using the LGM SSTs alone as opposed to the full LGM conditions.

Including the drop in sea-level and the LGM Northern Hemisphere ice-sheets in the control simulation produces a cooling response across the continents (Figure 7.4). The Australia-wide average has significant cooling in winter, and less cooling in summer, contributing to the enhanced seasonality shown by the full LGM simulation. There is regional and seasonal variation in the response in Australia. In winter there are significant reductions in temperature in all regions except the north, that shows a significant increase in temperature. In
summer the response in the north is reversed, with significant cooling, while the south west and east regions show some warming.

The increased extent of sea-ice suggested by CLIMAP produces little change in the temperature across Australia. The slight changes that do occur decrease the seasonality except in the south west.

For all of Australia the reduction of summer insolation at high latitudes leads to a reduction in the seasonality, contrary to the full PMIP simulation. This is the case in all climate regions, with warming in winter and cooling in summer. The region specified for the north of Australia would be expected to not respond to these changes as it is north of the tropic of Capricorn.

The carbon dioxide decrease at the LGM produces slight cooling in all seasons and regions except in the north, with the greatest cooling in the summer. This seasonal distinction might be due to the increased capacity for heat-loss at night after the surface has warmed strongly during the day in summer.

The boundary condition that produces the near-surface temperature response most consistent with the full PMIP LGM simulation is the CLIMAP SSTs. Just as in the full LGM simulation, there is a reduction in temperature in every region and both summer and winter, with an increase in the seasonality, in the control simulation with just the CLIMAP SSTs. The control simulation with the LGM change in atmospheric carbon dioxide concentration produces the next greatest temperature reduction in the Australia-wide, annual mean, but it is not significant, and the seasonal responses are small. The inclusion of the sea-level drop and Northern Hemisphere ice-sheets produces an all-Australia average cooling in summer and winter but the response is not consistent through the other seasons or in all regions. All other boundary conditions, when included in the control simulation alone, produce a small response. This analysis shows that the prescribed SSTs are driving the changes in seasonality as well as the majority of the temperature reduction.

7.3 Sensitivity of precipitation signal to changing boundary conditions

The number of LGM temperature reconstructions from proxies across Australia is limited, while there are many more examples of changes in the hydrological conditions at the surface, (e.g. Bowler et al. (1976); Kershaw (1986); Chen...
et al. (1993); Page et al. (2001); Cupper (2003)). Precipitation changes are a strong contributor to the changes in the surface moisture availability. The factors leading to precipitation, including the moisture of the air mass and uplift processes, are complex, and it is not always clear how each of the PMIP boundary conditions would contribute to precipitation shifts. The MUGCM result with the full LGM PMIP boundary conditions produce small regions of increased precipitation across Australia (Figures 4.4, 4.5 and 4.6), and there is a mixed response simulated by the different PMIP models (Figure 4.7). Exploring which of the LGM boundary conditions are driving the drying (and wetting) across Australia in the MUGCM will help understand what might have driven the precipitation changes at the LGM.

The rainfall response in each of the climate regions across Australia (Figure 3.15) for the annual mean, winter and summer are presented in Tables 7.4, 7.5 and 7.6, respectively. The east (SE1) and south east (SE2) regions are separated as their precipitation response is often of the opposite sign.

The annual average rainfall for the full PMIP simulation is significantly reduced in the north, central and far south east regions. In the south west there is a small reduction in precipitation, but in the east there is an increase. This is likely due to a hot-spot in the CLIMAP SSTs encouraging precipitation along the coast, as can be seen in Figure 4.4. There is a strong response in the north and east when the LGM SSTs are imposed alone. With just the CLIMAP SSTs, both the south east and south west of Australia see a reduction in rainfall, though it is not significant. There is a small but consistent increase in precipitation with extended sea-ice, suggesting that this pushes storms equatorward, and over Australia. The lowered carbon dioxide also shows a consistent response, with reductions in precipitation everywhere, in the north and east by quite large amounts, likely linked to reduced convection due to the temperature reduction as seen in Figure 7.3. The drop in sea-level produces a large reduction in precipitable water as was hypothesised in Chapter 4, and would thus be expected to reduce precipitation across Australia, and this is seen in every region.

The difference between the anomalies in each of the seasons suggest why the sea-level has such a strong effect on the simulation. In the sea-level experiment in winter (Table 7.5) there is a strong and significant reduction in precipitation across Australia in all regions, while in summer (Table 7.6) there is actually a small increase. In imposing the drop in sea-level, the large ice-sheets over
the Northern Hemisphere continents are also included. There is a very strong reduction in the precipitable water in the lowered sea-level experiment in the Northern Hemisphere in their summer, and, to a smaller extent some decrease in Africa, the sub-Continent and South America in the austral summer (Figure 7.6). The drier global atmosphere in JJA (and Australia) is the likely reason for the strong reduction in precipitation in this season.

The annual precipitation response to the LGM sea-ice imposed alone in the PD simulation is a consistent positive change across all regions, but in the seasons the change is not so consistent, with some small reductions in the east in winter (Table 7.5). It may be that the extreme change in the sea-ice in summer has indeed pushed a number of systems from the south farther north to affect the east and north of Australia, perhaps in the same way as Webster and Streten (1978) suggested that the sea-ice altered the long-wave pattern in the Australian region, leading to an increased number of cold outbreaks up the east coast. (This is shown in the next section).

The changes in response to the altered solar conditions are unclear. The reduction in carbon dioxide leads to a reduction in surface temperatures and the heat-lows that direct rainfall over northern Australia in summer might be expected to be weaker. The seasonal response reflects this, with reductions in the north, central and east regions in summer.

The seasonal precipitation response to the CLIMAP SSTs shows the only significant anomalies from the PD besides those in the sea-level experiment in winter. The significant changes are in the regions with seasonally higher rainfall. In summer (Table 7.6), it is in the north where there is a strong change, although there are also large reductions in central and eastern Australia. The strong reduction in the north in summer suggests a reduction in the amount of rainfall brought by the monsoon. In winter (Table 7.5), the significant changes are in the east, with very large increases due to the hot-spot in the CLIMAP SSTs (Figure 3.13), and reductions in the south east and south west. There are small increases elsewhere. The rainfall in the south of Australia is generally brought by storms embedded in the westerlies. The significant reductions across the south further support the theory of a shift in those storms.
### Table 7.4: Annual precipitation over different regions with different boundary conditions. Control total, and differences from control, mm/day. Bold numbers are significant differences at the 95% level.

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### Table 7.5: As Figure 7.4 but for JJA.

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7.4 Sensitivity of location of westerlies to boundary conditions

Using the low level zonal wind as an indicator of the meridional shift in the westerlies, Figure 5.5 shows the zonal component of the wind in the Southern Hemisphere for the PD and LGM. The shift in the boundary between the easterlies and westerlies in the Australian region has shifted south at the LGM, with the largest displacement in winter.

Figure 7.7 shows the zonal wind, zonally averaged across Australian longitudes (100-160°E) for winter. The LGM simulation clearly shows a southward shift in both the latitude of cross-over from easterlies to westerlies and also a southward shift in the latitude of the maximum westerlies. In the PD the region of maximum eastward movement, which might represent the track of the most active storms, sits right across southern Australia in winter, while at the LGM the magnitude of the zonal mean wind is greatly reduced over the Australian continent. The region of maximum westerly zonal wind in Australian longitudes has also broadened at the LGM.

In attempting to describe the drivers behind the possible conceptual circulations described in the literature, particularly from the dune evidence, it is useful to examine the shifts in the annual mean. Figure 7.8 shows the zonal average of the annual zonal wind between 125 and 145°E, the region where the dunes directions differ between the PD and the past. Like winter, there is a southward shift in the LGM simulation, and the SSTs are the main driver of this shift. At some longitudes, the sea-level contributes to the southward shift. No boundary condition besides the SST moves away from the PD curve by very much except at higher latitudes.

The two boundary conditions that create a strong response in the latitude of the zonal wind when applied alone in the PD simulation in both winter and summer are the sea-ice and the SSTs. The zonal wind in the Australian region has little response to all other boundary conditions.

7.4.1 Sea-ice

The suggestion that the Australian proxy evidence could best be explained by a northward shift in the westerlies is described by Harrison and Dodson (1993). The hypothesised LGM circulation change that would lead to such a northward
Figure 7.6: MUGCM precipitable water anomaly from the sea-level and Northern Hemisphere ice-sheet experiment. (a) JJA, and (b) DJF. Contour interval is 2 mm
Figure 7.7: Winter zonal wind at 850 hPa, zonally averaged from 100 to 160° longitude. Units: m s$^{-1}$. Simulations include PD, LGM, and PD with LGM sea-ice extent and PD with LGM SSTs.

Figure 7.8: Annual 850 hPa zonal wind, zonally averaged from 125 to 145° longitude in m s$^{-1}$. Simulations include PD, LGM, and PD with LGM sea-ice or SSTs or LGM sea-level (and Northern Hemisphere ice-sheets) or LGM CO$_2$ concentration or LGM solar input.
shift was believed to be driven by the extended sea-ice around Antarctica (Webster and Streten [1978], resulting in a northward shift in the belt of storms that encircle Antarctica and affect southern Australia. This response is much like that believed to have occurred in the Northern Hemisphere around the continental ice-sheets, (e.g. Kageyama et al. [1999b]). In the Southern Hemisphere however, there is no added altitude to the extended ice, while in the Northern Hemisphere the blocking effect of the LGM ice was believed to play a major role in re-directing the upper level storm-tracks equator-ward at the LGM.

Including only the LGM CLIMAP sea-ice extent in the PD MUGCM simulation would be expected to have an influence on the circulation as the new ice produces a barrier to ocean-atmosphere interaction, (Simmonds and Budd [1991]). The new sea-ice would block the energy provided by the relatively warm ocean to the atmosphere, and modify the the vertical profile of the wind. These factors would alter the stability regime, and limit the potential for storm development over the ice. The increase in sea-ice extent does indeed push the westerlies in the Australian region further north (Figure 7.7). This is particularly true in summer when the difference between the PD and LGM sea-ice is at its greatest (not shown). Thus the conceptual circulation response suggested by, for example Webster and Streten [1978] would have been accurate if there were no other changes to the boundary conditions at the LGM.

7.4.2 SST

The anomalies of the LGM SSTs reconstructed by CLIMAP from the PD (Figures 3.12 and 3.13) show a strong spatial variation. The change in meridional and longitudinal gradients would be expected to have a strong effect on the circulation.

Including just the CLIMAP SSTs in the PD simulation (the PD SSTs are used in the region under LGM sea-ice) has a strong influence on the zonal wind in the Australian region as shown in Figure 7.7. There is a marked southward shift in the winds, as well as a suppression of the peak westerlies compared to the PD and also the full LGM simulations.

The importance of the LGM SSTs on shifting the westerlies south is highlighted from analysis of the results of the PMIP simulations with mixed layer oceans. The average 2 m temperature pattern in each of the mixed layer experiments is quite different from the others, and also different from the CLIMAP
7.4 Sensitivity of location of westerlies to boundary conditions

SST reconstruction. The mixed layer ocean experiments show little change in the meridional placement of the westerlies at the LGM. This indicates that the CLIMAP SSTs are important in driving the shift in the westerlies seen in the simulations with fixed SSTs (Figure 5.13).

7.4.3 Discussion

The PD simulation including LGM sea-ice has westerlies that cross southern Australia further north than in the PD simulation with PD sea-ice, however, when the full LGM boundary conditions are applied, there is a strong southward shift in the westerlies. The southward shift is seen in all the LGM simulations with the PMIP models with fixed SSTs. For MUGCM the southward shift is due largely to the SST reconstruction from CLIMAP. Applying the LGM sea-ice in the PD simulation also results in stronger westerlies, while the westerlies in the PD simulation with LGM SSTs are not as strong. The Australian-region westerlies in the full LGM simulation (Figure 7.7) have a stronger peak than in the PD simulation with the LGM SSTs alone, perhaps showing the influence from the extended sea-ice, as the meridional temperature gradient to the south of Australia is steepened.

The result that the southward shift in the westerlies in the LGM simulation is driven by the CLIMAP pattern of SSTs north of the LGM sea-ice edge suggests that the southward shift is driven by tropical and subtropical processes, rather than the conditions at high latitudes. At present there has also been a shift in the westerlies affecting southern Australia. The dominant mode of mid- to high-latitude Southern Hemisphere variability is zonally symmetric, with anomalies of opposite sign in Antarctica and the mid-latitudes (Karoly et al. 1996; Limpasuvan and Hartmann 1999). A recent upward trend has been noted in this mode (Marshall 2003), along with the shift in the westerlies affecting southern Australia. Thompson and Solomon (2002) suggests that the driver of the recent changes is the polar stratospheric ozone depletion driving a series of dynamical shifts that lead to a southward shift in the northern-most extent of the westerlies. The response to ozone depletion is greatest in spring and summer, while the noticeable shift in the PD westerlies is in winter. The results here suggest drivers of winter shifts in the westerlies that are not linked to the high latitudes.

To better understand the shifts in the westerlies driven by the LGM SST
pattern, the changes aloft and the Hadley circulation are also considered. Figure 7.9(a) shows the difference in temperature zonally averaged across Australian longitudes (100-160°E) between the full LGM simulation and the PD while Figure 7.9(b) shows that between the simulation with only LGM SSTs and the PD. The anomalies south of about 50°S are very different in the two simulations. The minimal response in the SST simulation is due to the fact that where there is sea-ice in the LGM, but ocean in the PD, the PD SSTs were used. North of about 50°S the anomaly patterns are strikingly similar.

These results suggest that in the Australian region, although there is a strong temperature response at high latitudes in the full LGM simulation, the southward shift in the westerlies is predominantly due to the changes in the SSTs in the tropics and subtropics.

7.5 Modifications to LGM boundary conditions

7.5.1 SST

In the preceding analysis, the decrease in temperature simulated over Australia is not as great as the temperature depression suggested by LGM proxy evidence, and the most important boundary condition forcing this decrease is found to be the LGM SSTs. In this section the SSTs will be modified in ways suggested in the literature and the corresponding response in the Australian region will be assessed.

A number of new proxy measurements of the ocean surface temperature have been completed since CLIMAP. Mix et al. (2001) outlines a new program to produce a new gridded dataset of this new data. Guilderson et al. (1994) reconstructed SSTs from corals in Barbados and found that the LGM was 3 to 4°C cooler than CLIMAP. Temperature reconstructions from alkenones in eastern subtropical Atlantic, near the west African coast are cooler than CLIMAP also - from 0.7°C (Zhao et al., 1995) to 1.5°C (Chapman et al., 1996). Closer to Australia, in the Indian Ocean, the temperature reconstructions from alkenones (Sonzogni et al., 1998) are similar to CLIMAP. To assess how Australian temperatures respond to changes in the LGM SST magnitude and distribution suggested in the literature, these are applied in turn.
Figure 7.9: JJA MUGCM zonally averaged (110-160°E) temperature anomaly. (a) Full LGM simulation minus PD (b) SST only simulation minus PD Contour interval is 1°K, negative contours are dashed and the zero line is bold.
Australian region

The SSTs around Australia have been reconstructed by Barrows et al. (1996), Martinez et al. (1999) and Barrows et al. (2000), and presented on the Australasian Quaternary Data Base (AQUADB) web site. They are the same or cooler than the CLIMAP SSTs and, most significantly, do not include the anomalously warm ‘bulls-eye’ off the east coast. The cooling of the SSTs around Australia might be expected to have a large scale influence on the temperature of Australia. Including these SSTs in the Australian region and CLIMAP SSTs elsewhere, and running the LGM simulation with these updated SSTs, the differences from the PD are shown in Figure 7.10. The anomaly across Australia (PD extent) averages to -1.27°C, slightly less cooling than the standard PMIP SSTs. This indicates that this scale of change in the local SSTs have little influence on the mean annual temperature of Australia.

Figure 7.10: MUGCM anomaly of the annual temperature at the lowest sigma level. LGM simulation with the updated Australian region SSTs minus the PD simulation. Contour interval : 1°C, negative contours are dashed and the zero line is bold

What is of interest though, is that there is a slight increase in the Australia-wide, annual precipitation in this simulation (1.45 mm day$^{-1}$) compared to the LGM simulation with the full PMIP SSTs (1.43 mm day$^{-1}$, see Table 7.4). The total is still much less than the PD, 1.78 mm day$^{-1}$. Spatially, the increases in precipitation in the full LGM simulation compared to the PD are associated with the anomalously warm SSTs off the east coast, where enhanced convection, cloud and precipitation over the patch of warm SSTs extends inland (Figures 7.11 and 4.4(b)). With the removal of the warm SSTs, it might be expected that this precipitation would also be reduced, and the Australia-wide
average might decrease. Indeed, the rainfall and cloud on the east coast in this
simulation is reduced (Figure 7.12). However, the low-level cloud amount has
increased in a band from northern Queensland through central Australia. The
850 hPa annual wind anomalies from PD illustrate a shift in the anomalous
winds between the two simulations (Figure 7.13). With the full PMIP SSTs
there is anomalous on-shore flow across the east coast at the latitude of the
warm SST anomaly, where much of the atmospheric moisture is precipitated
out over the ocean. When the warm SSTs are replaced with cooler ones around
Australia, the anomalous on-shore flow is not as marked, but there are on-shore
anomalies right up the Queensland coast. Without anomalously warm SSTs
to encourage the atmospheric moisture to rain out, there is the potential for
the moisture associated with this anomalous on-shore flow to encourage cloud
and precipitation further inland, as seen in Figure 7.12, leading to the increased
precipitation in the LGM simulation with cooler Australian SSTs.

![Figure 7.11: MUGCM LGM annual low level cloud minus the PD. The mean
cloud is expressed as a fraction, from 0 to 1.0. Contour interval: 0.05]

**Global reduction in SST**

There have been re-evaluations of the CLIMAP cores along with results from
new cores in other regions and the CLIMAP results have been found to be
generally too warm. Rind and Peteet (1985) found that the tropical CLIMAP
SSTs are too warm to comply with the proxy evidence on nearby land and
Crowley (2000) suggested that a preliminary solution would be to lower the
temperatures everywhere by 1°C. This cooling was implemented, along with
the suggested reconstructions in the Australian region.
Figure 7.12: MUGCM LGM, with SSTs updated in the Australian region, annual low level cloud minus the PD. The mean cloud is expressed as a fraction, from 0 to 1.0. Contour interval: 0.05, negative contours are dashed and the zero line is bold.
7.5 Modifications to LGM boundary conditions

Figure 7.13: MUGCM annual 850 hPa wind anomaly for MUGCM simulations with (a) full LGM boundary conditions, and (b) full LGM boundary conditions with the SSTs updated in the Australian region. Units: $\text{ms}^{-1}$
7. Sensitivity to LGM boundary conditions

Figure 7.14: MUGCM annual differences in temperature for the full LGM simulation with the SSTs updated in the Australian region and the global CLIMAP SSTs cooled by (a) 1°C and (b) 2°C. Contour interval: 1°C
7.5 Modifications to LGM boundary conditions

Figure 7.14 shows the temperature anomalies with reductions of both the CLIMAP and updated Australian region SST reconstructions by 1°C and 2°C. It was found that as the SST decreased, the temperature of Australia correspondingly decreased. The Australia wide average anomaly is -1.27°C when only the local SSTs are changed, -2.71°C for a reduction in SSTs of 1°C, and -3.78°C with a reduction of 2°C.

The SST pattern is the same as after the Australian region SSTs have been updated, thus the temperature gradients in the SSTs will be the same. The temperature anomalies have a similar structure across Australia in all the simulations with cooler Australian region SSTs, with a band of strong cooling stretching from the northeast to the southwest. In a single column sense, there is no decrease in the amount of incoming solar radiation, or in the greenhouse carbon dioxide, however, the air advected off the oceans will be much cooler, and will provide cooling of the surface right across the continent. The hydrological cycle may also be modified.

The spatial pattern of cooling aligns well with the increased cloud across Australia noted in Figure 7.12 when just the Australian region SSTs are modified, and the same cloud pattern persists when the SSTs are reduced, with an increase in the amount of cloud when the SSTs are reduced by 1°C (Figure 7.15(a)), and then an increase in the extent of the cloud with further SST cooling (Figure 7.15(b)). The increased cloud amount is also linked to an increase in precipitation compared to the annual average anomaly with the LGM run forced with CLIMAP SSTs. The Australia-wide annual average precipitation anomaly with CLIMAP SSTs is -0.35 mm day\(^{-1}\), with the Australian region SSTs updated and all SSTs reduced by 1°C, the anomaly is -0.28 mm day\(^{-1}\), and with a further reduction in SST, the anomaly is only -0.12 mm day\(^{-1}\). Besides the advection of cooler maritime air over the continent, the increase in cloud cover and rainfall will also contribute to a reduction in temperature. The cloud cover will reduce the incoming solar radiation, and hence the day-time temperatures, while the surface will be wetter from the increased precipitation, increasing the surface cooling via evaporation.

The simulation of Australian temperature is more sensitive to the reduction of global and local temperatures by 1°C than to global temperatures reduced by a greater amount. The initial difference between no change to the CLIMAP SSTs and a reduction of 1°C is larger than 1°C(1.44°C) while the decrease with a global reduction of 2°C is less: 1.07°C. This non-linearity in response
Sensitivity to LGM boundary conditions is probably linked to the hydrologic cycle and clouds. As the global SSTs are cooled by 1°C, the cloud fraction increases markedly enhancing the cooling (e.g. compare Figure 7.15(a) with Figure 7.12), however with a further cooling, the cloud persists and expands spatially however the cloud fraction does not increase.

Changes to the global SST pattern

The SSTs reconstructed for CLIMAP may not have been as cool as the conditions at the LGM (as explored above) but there are also inconsistencies in the quality of the temperature reconstructions from core to core (CLIMAP, 1976), and hence the CLIMAP spatial pattern is likely not a perfect representation of the mean LGM SSTs. The gradient of temperature across the Pacific is linked to ENSO, and thus changes in this gradient will have strong implications for those parts of the globe whose climate is influenced by ENSO, such as the east and north of Australia. The tropical SSTs have also been shown to have a strong influence on the LGM climate (Yin and Battisti, 2001). Evidence from the depth of the thermocline across the Pacific was used by Liu et al. (2000) to suggest a zonal gradient across the tropical Pacific more accurate than the CLIMAP reconstruction. The gradient had a mean reduction of 3°C in the eastern tropical Pacific and 1°C in the west. This was included in the SST pattern in the MUGCM by determining the zonal gradient of the mean temperatures 10° either side of the Equator in the CLIMAP SSTs, and adjusting for any differences with the gradient of Liu et al. (2000). The largest differences were in December and January, while the smallest were in August and September. The annual change implemented is shown in Figure 7.16.

With the new tropical gradient in the LGM simulation, the annual average near surface temperature shows strong cooling in the north east of Australia, with the same values as the reduction of global SSTs by 1°C Figure 7.17. In the south east, west and south west there is little temperature change. The updated SSTs in the Australian region were included as well as the change to the tropical SSTs, so comparison with the PMIP simulation with corresponding updated Australian SSTs will be considered. The strongest change is in summer with decreases in temperature between the regular PMIP simulation (with updated Australian region SSTs) of up to 4°C in the east. Cooling extends across much of the country, but there is also warming in the south west. In autumn there is cooling by up to 1°C in the north but warming of up to 1°C in the far
7.5 Modifications to LGM boundary conditions

(a) LGM, updated Australian region and CLIMAP SST minus 1°C

(b) LGM, updated Australian region and CLIMAP SST minus 2°C

Figure 7.15: MUGCM low level cloud anomaly for the full LGM simulation with the SSTs updated in the Australian region and the global CLIMAP SSTs cooled by (a) 1°C and (b) 2°C. The mean cloud is expressed as a fraction, from 0 to 1.0. Contour interval: 0.05, negative contours are dashed and the zero line is bold.
7. Sensitivity to LGM boundary conditions

Figure 7.16: Improved zonal gradient in the Pacific SSTs minus CLIMAP, with updated Australian region. Contour interval: .5°C

Figure 7.17: Annual average anomaly of temperature at the lowest sigma level with improved zonal gradient in the tropical Pacific SSTs, updated Australian region SSTs and all other PMIP boundary conditions. Contour interval: 1°C
south. Winter and spring show moderate cooling right across the continent - up to 1.5°C in winter and 1.0°C in spring. These responses are very strong, surprisingly also in winter and spring when the changes to the tropical SSTs was small, indicating just how important both the magnitude and gradient of the equatorial Pacific SSTs are.

**Shift in westerlies with SST changes**

The annual zonal wind at 850 hPa was averaged across 125 to 145° longitude for each of the tests with changing the SSTs. The full reduction of the SSTs by 1°C or 2°C might be expected to modify the thermal structure of the atmosphere, but with no change in gradients, it is no surprise that there is little shift away from the curve with the full LGM boundary conditions. The change in the temperatures in the Australian region might be expected to produce a change in the zonal wind in the region, but little is seen. When the gradient across the Pacific suggested by Liu et al. (2000) is implemented into the CLIMAP SSTs, there is a strong shift in the zonal wind in the Australian region as seen in Figure 7.18.

There is minimal gradient across the tropical Pacific in the CLIMAP reconstruction in winter, but strong cooling. In summer, there is a weak El Niño-like tropical SST pattern in CLIMAP, which the imposed gradient shifts to a more La Niña-like configuration. This had a large effect on the temperatures across the regions of Australia influenced strongly by ENSO in the PD. The new gradient leads to an even stronger southward shift of the westerlies in the Australian region. The southward shift is most likely influenced, not by the shift in the Walker circulation, but by a further weakening of the meridional temperature gradient.

### 7.5.2 Atmospheric Carbon Dioxide concentration

The decrease in atmospheric CO$_2$ at the LGM has a small cooling effect in winter in the MUGCM simulation (Table 7.2), and produces half the cooling of the full PMIP conditions in south west Australia in summer (Table 7.3). The difference in response in the seasons is probably linked to the increased heat stored in the surface during the daytime in summer, compared to winter, and the increased potential for losses during the night. The reconstruction of LGM atmospheric CO$_2$ concentration from air bubbles in Antarctic ice by Petit et al. (1999) and
Figure 7.18: Annual 850 hPa zonal wind, zonally averaged from 125 to 145° longitude in ms$^{-1}$. Simulations include PD, LGM and LGM with the Australian region SSTs updated, and the tropical Pacific SST gradient modified to that suggested by Liu et al. (2000) (PMIP Oz Grad)
Augustin et al. (2004) have constrained the value well. However there is some error margin and there may be non-linear responses by the atmosphere at these low concentrations, thus it is worthwhile to investigate how the simulations respond to a value within the error margin, and one well below the suggested LGM concentration. The full PMIP LGM simulation has atmospheric CO$_2$ set at 200 ppmv, so to test the sensitivity to CO$_2$ changes it was set to 180 ppmv and then 160 ppmv with all the other LGM boundary conditions as for the full PMIP LGM simulation.

The response in surface temperature to these reductions in CO$_2$ concentration is not linear, nor is it consistent across Australia. The annual average shows mixed changes for the different climate regions, with a reduction of a third of a degree in the southwest between 200 ppmv and 180 ppmv, but an increase of 0.08°C in the central region. Reducing the concentration further produces little response. In summer there is actually warming in the north of Australia from the 180 ppmv to the 160 ppmv simulation. The largest cooling with decreasing levels of atmospheric CO$_2$ concentrations is in winter, enhancing the seasonality further. The reduction to 180 ppmv produces the biggest change with reductions of up to half a degree in all the regions. Reducing the concentration further produces little change. Thus if the CO$_2$ concentration was 180 ppmv rather than 200 ppmv with all other LGM boundary conditions the same, the MUGCM produces a further cooling in winter across Australia.

Assessing the annual average mean zonal wind at 850 hPa, zonally averaged across Australian longitudes (125° to 145°E), there is little shift in the westerlies from the full LGM simulation. There is a slight northward shift, compared to the full LGM simulation, for both 180 and 160 ppmv between 30 and 37°S, but only the 160 ppmv continues to show this northward shift to higher latitudes. This may suggest that as the continent cools, the westerlies track slightly further north than they might otherwise.

### 7.6 Chapter summary and conclusions

In this chapter the major drivers of the changes in Australia’s precipitation, temperature and circulation in the LGM simulation were assessed. The control simulation with only the SSTs changed to those reconstructed for the LGM in CLIMAP (1981) produces a response in Australia quite similar to the full LGM simulation. The increase in seasonality is also introduced from the SSTs. In
winter the drop in sea-level (with the Northern Hemisphere ice-sheets included) produced a strong change in the near surface temperature and precipitation. The decreased atmospheric carbon dioxide produced a small, but insignificant cooling and drying in all but the north region in both summer and winter. The change in SSTs north of the LGM Antarctic ice edge also produced the same southward shift in the westerlies as the full LGM simulation, while the LGM sea-ice produced a northward shift in winter.

The full PMIP LGM simulation does not produce a cooling in any season on par with those suggested by Miller et al. (1997). Thus steps were taken in this chapter to determine if changes in the prescribed SSTs, that have the major influence on the changes in the Australian climate, or in the level of atmospheric carbon dioxide, can bring the temperature response in Australia more in line with the proxies.

Reducing the atmospheric carbon dioxide concentration beyond the suggested level in the PMIP LGM simulations produces further cooling across Australia, particularly in winter. The response has a threshold, with reductions beyond the range suggested as reasonable for the LGM producing little further cooling. From this sensitivity test it seems that the more likely level of atmospheric carbon dioxide level for the LGM is at the lower end of the suggested range.

The CLIMAP SSTs have some limitations, and changes to the SSTs, as suggested in the literature, were added to the CLIMAP SSTs and simulations were then run including the other LGM boundary conditions. Changing the SSTs in the Australian region to those of Barrows et al. (1996), Martínez et al. (1999), and Barrows et al. (2000), actually produces less temperature depression across Australia than the usual PMIP SSTs, due to a shift in the cloud and precipitation response. Reducing the local and global temperatures by 1°C produces temperature reductions of greater than one degree, but a further global reduction by 1°C does not produce a proportionally strong response.

It was found that it was not just the reduction of temperature globally that produces a decrease in the Australian temperatures, but modifications to the zonal temperature gradient across the Pacific. A change to the zonal gradient in the tropical Pacific was made because reconstructions of the thermocline indicate that it is a more accurate representation of the LGM ocean surface. This leads to enhanced cooling across much of Australia, particularly in summer. Thus the Australian LGM temperatures were highly responsive to changes in
the eastern Pacific, as is the case today. For an accurate simulation of the Australian LGM climate with an atmospheric GCM, accurate reconstructions in the eastern Pacific are of paramount importance.

The fact that, even with strong modifications to the boundary conditions, beyond the suggested changes to CLIMAP, the model still does not simulate temperatures as cool as those reconstructed from proxies suggest that the model is failing to capture some further driver of the cooling. This may come from the oceans, since this is only an atmospheric model, and, with the next phase of PMIP with coupled ocean-atmosphere models, this suggestion can be analysed.

The shifts in the westerlies in the Australian region are found to be driven by the meridional SST gradient, north of the Antarctic sea-ice edge. This has strong implications for changes in the climate at present, where the global distribution of the temperature response to the enhanced levels of greenhouse gases might also shift the mean westerlies in the Australian region to the south.

Although the CLIMAP SSTs have known shortcomings, and the sensitivity experiments that modify the mean SST or SST pattern produce temperatures over Australia more in line with the proxy evidence, at this stage CLIMAP remains the only comprehensive, consistent, gridded SST data-set for the LGM.
7. Sensitivity to LGM boundary conditions
Chapter 8

Dunes as a proxy for wind

8.1 Introduction

Drawing together the information about local winds from the many continental dune fields can provide clues as to the large scale circulation changes in the Australian region. From the dune ages and evidence of aeolian activity at lakes outlined in Chapter 2, it is clear that there was dune activity at the LGM. The relict dunes, and the seemingly anti-cyclonic circulation pattern that their orientations suggest across the continent, appeal as a direct proxy of the past circulation, but using dunes as proxy evidence for past winds requires steps beyond determining the age and orientation of the dune. In this chapter the link between the near surface winds and dune orientations will be considered, accounting for some of the modifying factors.

Factors that modify the link between winds and dune orientation include the local orography, the wind strength and direction, the type and amount of sediment available, vegetation, groundwater and surface moisture. Understanding how each of the limiting factors vary with seasons and how they modify the orientation of the dunes is fundamental to understanding how dunes can be used as a proxy for paleo winds.

The dune orientations that will be compared to the winds and calculated ‘dune directions’ have been digitised from Wasson (1986), shown in Figure 2.6.
8. Dunes as a proxy for wind

8.2 Formation of linear dunes

The range of dune types was discussed earlier in this thesis with linear dunes being the most common across the Australian landscape. As linear dunes are the major indicator of orientation across many of Australia’s dunefields, it is important to understand the controls on their formation and how those controls relate to the wind and other factors.

To model dune formation it is important to understand how the wind direction relates to the orientation of linear dunes. To answer this, the method of formation must be understood. There is still no general consensus on the exact method of formation of linear dunes, nor if there is only one method for all different linear dunes (Tsoar, 1989; Tseo, 1993).

Two basic models have been proposed for the wind regime that forms linear dunes. Wiggs (2001) provides a good review of these two methods. One involves ‘rotors’ or helical vortices in the wind that heap sand out of the swales (inter-dune hollows) and onto the dune slopes. The other is via a wind regime that is variable, but all winds contribute to the same direction downwind (e.g. they all have a westerly component). This wind regime was termed ‘bi-directional’ by Fryberger (1979), and that will be the term used to describe it here. Winds will then heap sand onto the dune first from one direction, and then from the other, extending the dune downwind in the resultant wind direction.

One argument against helical vortices is the lack of field measurements of this phenomenon. This may be due to their transience, although there is evidence of cloud streets aligned with dune forms, which may be an atmospheric expression of the presence of such rotors, (Nichol and Grove, 2001).

‘Cross-bedding’ in linear dunes strongly supports the idea of the influence of a variable wind direction in dune genesis (e.g. Tseo (1993) and Bowler, pers. comm. (2003)). The layers found in the dunes are angled first from one direction, then another. In a wind regime with strong winds from different directions, but both with some contribution to the downwind direction, it is easy to see how the crossbed layers are laid down. Downwind extension would still occur, as the dune modifies the boundary layer flow to transport new material along the dune flank. The ‘cross-bedding’ provides compelling evidence that linear dunes most likely form under a variable wind regime.

Further evidence that linear dunes are likely formed by a bi-directional wind regime comes from computer models of the dune formation process. Werner
8.3 Limitations on dune development and orientation

8.3 Limitations on dune development and orientation

As mentioned previously, there are a number of factors that will modify a dune’s development and orientation. The analysis in this chapter will use meteorological data, and so the limitations linked with the wind or the hydrological balance can be considered, but a number of more local factors that cannot be accounted for are touched on here.

Dune extent is often limited by the surrounding topographical features. Wasson (1986) gives a broad description of the environment of each of Australia’s dunefields (see Figure 2.6 for desert names). The Mallee, Simpson and Great Sandy dunefields are in large flat basins, and the dunes in the Simpson and Great Sandy deserts extend for many kilometres downwind, with little interruption. The dunes of the Tanami, the Great Victoria and the southern part of the Gibson Deserts as well as south-west Western Australia are mixed with other topographic features, such as ridges, low ranges and valleys. These features limit the extent and possibly modify the orientation of the dunes that form there.

An example of dunes changing their orientation or extent due to the presence of orographic features is evident around Lake Lewis. The dunes in this region trend from the south east to the north west, except near the range to the north of Lake Lewis, where they are oriented along the range, (English, pers. comm. 2000).

The sediment supply has been suggested as a further factor modifying a dune’s final form (Wasson and Hyde 1983). However Rubin (1984) suggests that it is a secondary factor, and the guidelines laid out by Wasson and Hyde (1983) do not always apply. Since existing dunes are being considered in this thesis, it is assumed that there was an adequate supply of sediment for their...
formation.

The sediment that forms Australia’s dunes includes quartz sand and sand-sized pellets of clay or gypsum. Quartz grains that were once carried and deposited by rivers form the major source for dunes in the Great Victoria Desert and the north and east of the Simpson Desert. Pellets of clay or gypsum are found in the lunettes and linear dunes in the Mallee, south-west Western Australia, and in the south of the Simpson Desert.

The method of pellet formation varies and thus the presence of pellets in a dune can signify a range of possible environments for their formation. Pellet formation often involves salts and high groundwater levels (Bowler 1973; Bowler and Wasson 1984; Chen et al. 1991), indicating a wetter environment for initial formation before dessication and deposition. Wasson (1983) suggested that strong winds are required ‘to overcome hygroscopic attraction between the pellets’. Methods that do not involve high water tables were suggested in Wasson (1986), where blown salt may be sufficient for the formation of pellets. Although the methods of pellet formation vary, their presence provides clues to the environment of dune formation.

The composition of a dune will affect its stability. Although clay pellets are durable (with some even being transported in creeks (Wasson 1986)), their hygroscopic nature and subsequent coalescence effectively stabilises dunes in which they lie. This is in contrast to a loose quartz core, which may be completely reworked with a new period of strong wind.

The dune type can reflect the environment at the time of formation. For example, lake lunettes form during drying phases following high lake levels, but the extension of dunes away from lakes and water courses requires dry conditions.

Thus the timing of dune building may differ around the country, depending on the composition and source of the grains that form them. Those consisting of pellets may require specific hydrological conditions that do not coincide with the wind or vegetation controls limiting the movement of quartz sand. In the development of the equations for sediment transport below, it is assumed that all sediment is available for movement, and will move in dry, windy times.
8.4 Modelling of sediment transport

Not all wind will shift sediment and help create dunes. An understanding of how wind shifts sediment will help in exploring how dune orientation relates to the mean wind. Numerical models of the mechanics of sediment transport, in part derived from an empirical understanding of sediment movement, will begin to provide insight into how the mean wind relates to the sand-shifting wind. Bagnold (1941) is the major text on the theory behind sand movement, and many of the subsequent models are based on this work.

Bagnold (1941) found that grains move in three ways - suspension, creep and saltation.

a) Suspension occurs when a lightweight grain becomes suspended in the air aloft, and may be carried many kilometres downwind. This sort of transport is evident today in dust storms such as the huge dust cloud that engulfed Melbourne in February 1983 (Australian Bureau of Meteorology, 2004), or those that swept across much of the Australian eastern seaboard during the El Niño of 2002 (Watkins and Salinger, 2003). Marine cores in the Tasman shows evidence of dust transported in this way thousands of years ago (Hesse, 1994; Hesse and McTainsh, 1999).

b) Creep is sand slipping down a dune face, which is the result of gravity on a loose, sloping sand bed. The amount of creep is strongly dependent on the angle of the bed, grain size and any cementing attributes of the surface, such as soils, moisture or vegetation.

c) Saltation is the term used for a grain’s movement in an arc from the surface. This is the major method of sand transport on dunes, (Bagnold, 1941).

Saltation can occur once a certain wind speed has been reached and perpetuates as a single grain lands and potentially ejects other grains downstream, resulting in a cloud of grains being transported downwind. The transport of sediment goes through three stages, both in these models and in wind tunnel experiments. The first is an entrainment phase, where the particles are initially lifted by the wind, followed by a stage of ‘overshoot’, where the saltation has reached a maximum, but the wind profile has not yet been modified by the saltation, and an equilibrium where the transport is generally constant.

Shao and Li (1999) numerically modelled the process of saltation using a large eddy simulation, a Lagrangian model for particle motion and parameterisations for aerodynamic entrainment and particle surface interactions. They
modelled each of the stages of particle movement: 1. particle entrainment by aerodynamic shear; 2. particle trajectory; 3. particle rebound and entrainment by splash; as well as the modification of the wind profile due to particle momentum transfer. This model accurately matches the outcome of the wind tunnel observations of [Shao and Raupach (1992)] for values of friction velocity, $V_*$, greater than about 0.4 ms$^{-1}$. The model of [Shao and Li (1999)] assumes a neutral atmosphere, and a logarithmic wind profile:

$$ V = \frac{V_*}{\kappa} \ln\left(\frac{z}{z_0}\right) $$

where $V$ is the wind in the mean direction, $V_*$ is the friction velocity, $\kappa$ the von Karman constant, $z$ the height, and $z_0$ is the roughness length. Once saltation begins, the lower air layers are broken into two regions - one near the surface with reduced friction velocity, as the momentum of the wind is reduced by the presence of the sand grains, and a layer above that which has an increased roughness length, and correspondingly modified friction velocity. They found that the friction velocity in the near surface layer dropped to about one tenth of its former value. This is illustrated well in Figure 3 from [Shao and Li (1999)].

The model of [Shao and Li (1999)], and others like it, are calculated on fine grids - far finer than is feasible to use in a global model. The models also simulate all aspects of saltation from initiation to equilibrium. To define a resultant dune direction a model of the sand shifting potential at equilibrium is required. The wind data that will be analysed here is for less than twenty years, while a dune may take many hundreds of years to fully develop. To create some sort of ‘mean’, each wind measurement is taken as blowing for long enough to bring the sand movement to equilibrium.

There are many models of the mean saltation transport of sediment, including [Bagnold (1941)], [White (1979)], [Fryberger (1979)]. Most of the models are based solely on the wind speed as a factor needed for sand movement, and do not allow for other factors. In this section the method of [Bagnold (1941)] and [Fryberger (1979)] will be described for application to gridded data and GCM results. The limitation of soil moisture will then be considered and an equation including this will be defined.
8.4 Modelling of sediment transport

8.4.1 Wind speed

Wind speed is a major factor in many of the equations for the mean sand shifting potential. Bagnold (1941) found that there is a threshold velocity that must be reached before sand will move. Dune orientation is thus not necessarily aligned to the mean wind.

The equations that Bagnold (1941) derived for the potential, or maximum, sand movement, expressed as the weight of sand per unit area shifted by the wind under perfect conditions after the saltation process has reached equilibrium ($q$), are described below. They assume a neutral boundary layer, as used by Shao and Li (1999) (Equation 8.1), a flat surface and dry sand. The equilibrium sand shifting potential, $q$, is related to the cube of the wind.

$$q = C \sqrt{\frac{d}{D}} \frac{\rho}{g} V_*^3$$

$$D = \text{grain diameter for standard 0.25mm sand}$$
$$d = \text{grain diameter of given sand}$$

$$C = \begin{cases} 
1.5 & \text{for nearly uniform grains} \\
1.8 & \text{for naturally graded grains (dunes)} \\
2.8 & \text{widely varying grain size} 
\end{cases}$$

$q$ is in units of tons per metre per second, $\rho$ is the atmospheric density, $g$ is gravity and $V_*$ is the modified friction velocity after the equilibrium of sand movement has been reached.

The size and mixing of the grains has an effect on the wind’s ability to influence the surface. For well sorted grains, as the grain size becomes smaller, the threshold velocity reaches a minimum when the grain is approximately 0.08 mm in diameter. If the grain is smaller than that, the threshold velocity rises again, until, for very fine dust, no wind will shift it, unless there is a disturbance of the surface. Mixed grains require less wind to shift the smaller grains initially, as the larger grains provide a means of breaking up the wind and disturbing the surface, up to a point, where the larger grains ‘protect’ the smaller grains from the wind (Bagnold 1941). Australian dunes are dominantly composed of naturally graded, sand-sized clay pellets and quartz (0.15 - 0.3 mm) (Bowler, pers. comm. 2001).

To apply equation 8.2 to actual anemometer height data, $V_*$ is expressed
at a reference height following the steps outlined here. Assuming a neutral boundary layer, and a logarithmic wind profile, (Equation 8.1), then:

$$V_* = \frac{V_\kappa}{\ln\left(\frac{z}{z_0}\right)}$$  \hspace{1cm} (8.3)

where $V$ is the wind speed measured at the anemometer height. Saltation begins once the impact threshold, $V_t$, has been reached. The impact threshold is the wind speed found experimentally at which a surface disturbance will continue downwind. It varies with grain size; for a grain size of 0.25 mm, $V_t$ at 1 m above the surface is 1.9 ms$^{-1}$. After the saltation has reached equilibrium, $z_0$ increases, and is termed $z'_0$. The change varies depending on the grain size and distribution, about 3 mm for small grain even sand, and about 8 mm for mixed sand. Now

$$V'_* = \frac{(V - V_t)_\kappa}{\ln\left(\frac{z}{z'_0}\right)}$$  \hspace{1cm} (8.4)

for $V > V_t$

With some assumptions, the sand shifting potential can be calculated from actual wind at a certain height, say 10 m. Assume naturally graded, medium sized dune grains, and $z'_0 = 0.01$ m, then $\frac{z}{z'_0} = 0.058$ and $V'_* = 0.058(V - V_t)$. Cubing, $V'_*^3 = 1.9 \times 10^{-4}(V - V_t)^3$. Then from Equation 8.2, for this sand type, $\frac{d}{D} = 1$ and $C = 1.8$. Gravity is set to 9.8 ms$^{-2}$ and $\rho = 1.2$ kg/m$^3$, the density of dry air for average annual conditions in inland Australia (22$\degree$C). Equation 8.2 then becomes:

$$q = 4.3 \times 10^{-5}(V - V_t)^3$$  \hspace{1cm} (8.5)

Where:

- $V$ is velocity in ms$^{-1}$ at 10 m
- $V_t$ is the threshold velocity

Using only the winds above the threshold velocity and then effectively cubing the wind will give increased weight to stronger winds. This will modify both the magnitude and direction of the resultant.

Fryberger (1979) also applied the Bagnold (1941) sand shifting equations to actual wind data. Recognising the variety of conditions at the surface, such
8.4 Modelling of sediment transport

as the grain size, that are needed for the equation of Bagnold (1941), and the
difficulty in obtaining such a comprehensive dataset across different dunefields,
Fryberger (1979) chose to remove those limitations and hence chose a proportional equation for sand shifting, based solely on the wind strength:

\[ q \propto V^2(V - V_t) \]  

(8.6)

Using real data to estimate \( q \), Kalma et al. (1988) calculated \( q \) for when the wind is in certain wind and speed categories, and termed it the total drift potential (TDP, in units m\(^3\)s\(^{-1}\)). Equation 8.7 is simply equation 8.6 multiplied by \( t \), the percentage of time that the wind is in certain wind and speed categories.

\[ TDP \propto V^2(V - V_t)t \]  

(8.7)

Kalma et al. (1988) used equation 8.7 to determine the potential for erosion in each season across Australia. This will be the equation used in further analysis here.

8.4.2 Wind directionality

Throughout the course of the year winds will shift direction in most places in Australia, the degree to which the wind direction varies is termed the ‘directionality’. The equations of Bagnold (1941) for the sand shifting potential were deduced from short term experiments, where the wind direction did not change. To gain an appreciation of the winds forming the dunes across Australia at present and in the past, the full spectrum of winds throughout the diurnal and seasonal cycle is used.

Fryberger (1979) defined the types of dunes that will form by the strength of the wind and degree of directionality. The TDP as defined above, was calculated with instantaneous winds first in the zonal direction, termed \( q_u \) and then the meridional, \( q_v \). The method of combining the zonal and meridional component results in the TDP, as in Equation 8.7 when the vector is calculated at each instant: \( TDP \propto \sqrt{\sum q_u^2 + \sum q_v^2} \) and the means can be calculated for all the wind data, then the vector calculated, giving the Resultant Drift Potential, \( RDP \propto \sqrt{(\sum q_u)^2 + (\sum q_v)^2} \). These will only be equal if the wind is always from the same direction, otherwise \( RDP \) will always be smaller. The ratio of these, \( RDP/TDP \), gives a degree of directionality.
The strength and directionality of the wind is not the only limiting factor on dune formation, activation, extension and final orientation. Other factors that have been considered above include the local orography, sediment supply, type, size and sorting. Below the binding force of soil moisture will be considered, and included into the sand shifting equations, as well as a comment on vegetation.

8.4.3 Soil moisture and vegetation

Increases in soil moisture will increase the value of $V_t$ in Equation (8.5). Moisture in the sand is one factor that helps to bind the grains together. Fecan et al. (1999) extended the study of McKenna-Neuman and Nickling (1989) to give a general relationship describing the influence of wetness on binding sand at the micro scale and found that the inter-particle capillary forces are the most important binding force. The influence of this can be represented as increasing $V_t$ to $V_{tw}$, assuming there is no change in the roughness length with wetting. Here, $V_{tw} = f_w \times V_t$, where

$$f_w = \sqrt{(1 + 1.21\nu^{0.68})}$$

(8.8)

and $\nu$ is the gravimetric soil moisture percentage. Both MUGCM and NCEP2 provide volumetric soil moisture.

Volumetric soil moisture is the volume of water compared to the total volume. Gravimetric soil moisture is the weight of the water compared to the weight of the sand. To convert from volumetric to gravimetric soil moisture, the depth of the surface soil moisture layer and the maximum proportion of water that it can hold must be known. Since it is only the very top layer of sand that is deflated by sand shifting wind, in the MUGCM it is only the surface soil moisture that is considered. NCEP2 surface soil moisture has a depth of 10 cm and a maximum water volume proportion of 0.43. MUGCM has a surface layer with a depth of 0.5 cm and a maximum water proportion of 0.40. The proportional weight of the water is calculated by multiplying the volumetric soil moisture by 1.0 g cm$^{-3}$, and dividing by the proportional weight of the sand. The proportional weight of the sand is calculated using the bulk density of the soil, taken here as a value for sand, 2.84 g cm$^{-3}$, multiplied by the proportion of the volume that the sand fills, which is 1.0 minus 0.43, the maximum volume of water (10 cm / 4.27 cm). The ratio is multiplied by 100 to create a percentage.
8.4 Modelling of sediment transport

Figure 8.1: Six hourly volumetric soil moisture for June from one year. a) For top 10 cm from NCEP/DOE Reanalyses II (NCEP2), 1995, b) MUGCM, for top 0.5 cm, $W_g$. Letters A-F refer to a gridpoint from each of the climate regimes across Australia, Figure 6.5

\[ \nu = 100 \frac{w_g}{(1 - 0.43) \times 2.84} \]  

(8.9)

where $w_g$ is the volumetric soil moisture content.

The volumetric soil moisture for the top 0-10 cm in the NCEP2 has a longer memory than the top 0 to 0.5 cm in the MUGCM, and the values remain higher longer, as shown in Figure 8.1. This will reduce the sand shifting potential a greater proportion of the time in NCEP2 than in the MUGCM.

The proportional equation, including soil moisture is:

\[ q \propto V^2(V - V_{tw}) \]  

(8.10)

Vegetation will also limit the movement of sand, and thus the re-mobilisation of dunes will only occur given conditions able to overcome the limits imposed by the presence of any vegetation. [Ash and Wasson (1983)] suggests that vegetation in the semi-arid interior of Australia is limited by the moisture availability, which is linked to the ratio of the actual to the potential evaporation. [Wang et al. (2004)] also found a strong link between the potential evaporation and the temporal variability of sand mobility in China. It is extended periods of high
potential evaporation that will eventually stress a plant (Rind et al. 1990). The ratio of actual to potential evaporation can be expressed in terms of the soil moisture. In Chapter 6 the potential evaporation \((E_p)\) was estimated from the actual evaporation \((E)\) in the model using the soil moisture: \(E_p = \frac{w_{sat}}{w_g} E\), thus \(w_g = w_{sat} \frac{E}{E_p}\). Ash and Wasson (1983) proposed an equation for the mobility of sand given the square of the number of days with the wind above a threshold multiplied by \(\frac{E_p}{E}\), which, given the details above, is the inverse of the soil moisture.

The MUGCM simulations considered here are assumed to be at equilibrium, thus any shift in soil moisture will have a permanent affect on the amount of vegetation. As the annual soil moisture is lower in the LGM simulation, it automatically shows that there is an increase in dune mobility. The quicker response time to soil moisture changes shown by changes in the inter-particle capillary binding forces contributing to modifying the threshold velocity reveal seasonal variations that the vegetation changes would not. Thus the vegetation changes have not been included explicitly here, but the inclusion of the soil moisture will implicitly include the influence of vegetation, as the LGM simulation will have less soil moisture in the long-term mean.

### 8.5 Dune Type from Present Day Wind Spectrum

The equation for the mean sand shifting potential (Equation 8.7) and the measure of directionality described above were used by Fryberger (1979) to define possible dune types from the wind regime. The sand shifting potential and directionality of the wind were categorised and compared with the actual dunes in various regions around the globe, including Australia, to define limits for each dune type.

Fryberger (1979) defined three energy categories: low, mid and high energy. Values of the total drift potential for low energy are less than 200 m\(^3\)s\(^{-1}\), mid is between 200 and 399 and high, greater than 400 m\(^3\)s\(^{-1}\). Three categories of directionality were also defined, described as: uni-directional, bi-directional and multi-directional. Unidirectional has the ratio \(RDP/TDP\) greater than 0.8, bi-directional is between 0.3 and 0.8, while multi-directional is less than 0.3. The term ‘bi-directional’ used by Fryberger (1979) simply refers to the
range of $RDP/TDP$. Linear dunes are most often found in mid- to high energy wind regimes with directionality in the ‘bi-directional’ range.

With the availability of global wind data from the NCEP/DOE reanalyses II (NCEP2) reanalysis, a new opportunity has arisen to examine the global wind regime and directionality as defined by Fryberger (1979). Figure 8.2 can then be quickly assessed to determine the regions where different dune types are likely to form. The same categories as used by Fryberger (1979) were used here, using 20 years of 6 hourly output of the 10m winds from the NCEP2.

Figure 8.2: Global wind regimes, using the equation of Fryberger (1979) with 10 m winds from the NCEP/DOE reanalyses II (NCEP2) reanalysis. There are nine categories. Red to orange high energy wind regime, greens mid, blue and purple low. Red = uni-directional, dark-orange = bi-directional and light orange = multi-directional. Pale green = uni-directional to dark for multi. Mid blue = uni-directional, dark blue = bi-directional and purple = multi-directional.

Figure 8.2 shows that most regions in the tropics are in the low wind strength categories, with uni or bi-directional directionality. The subtropics, where many of the world’s dune fields lie, show more variability. In Australia, the north and east coastal regions are in a low wind regime, while most of the arid and semi-arid regions (where the dune-fields lie) are in a high or mid- energy category. A bi-directional wind regime is dominant across most of Australia. The bi-directional wind would encourage linear dune formation and the high energy wind would be conducive to dune building today. The result matches with the prevalent dune type in Australia, but at present observations have shown that there is only limited sand shifting and dune building across Australia.
This indicates that the wind regime may be appropriate, but there are other limitations on dune development.

### 8.6 Comparison of Present Day wind and dune orientation

In the section above the type of dune most likely to develop in all regions of the globe was determined from the wind spectrum. The result matched the dunes present today across much of Australia. Further information about the wind regime under which Australia’s dunes formed can be gained by appreciating how the direction of the sand shifting resultant differs from the mean wind, and how both compare with the orientation of relict dunes and present day sand drifts.

Brookfield (1970) and Fryberger (1979) assess how the orientation of the linear dunes match the results of sand shifting equations (including only wind strength as a limitation) from data at a few sites in Australia’s arid region. Blumberg and Greeley (1996) did a similar analysis with GCM output, and compared with satellite pictures of the dunes in the Simpson Desert. All found that the vector of sand shifting potential did not align perfectly along the line of the dunes, however they were comparing with relict dunes, and they also only used a very small number of years in their wind analysis. Kalma et al. (1988) present the results of the sand shifting equation (equation 8.7 here) as an indicator of the potential for erosion using 3pm station data from right around Australia, including the direction of the resultants, but they did not make a comparison with dune orientations. Not only did Kalma et al. (1988) consider the full annual resultant, but also the seasonal variation.

#### 8.6.1 Present day seasonal vectors

The dune orientation of Wasson (1986), shown in Figure 2.6 is compared with the mean monthly NCEP2 winds from the mid month of each season in Figure 8.3. The maps of Australia are cropped to best highlight the orientation shifts at the dune sites. The dunes have their closest match in the far north and north west with the April and July winds, however the wind vectors in January associated with the monsoon in these regions align poorly with the dunes. In the Simpson Desert and the south and east of the Great Sandy Desert the dunes
align well with the mean winds in all seasons. In the south of the continent the wind vectors are southerly in all seasons except winter. The annual resultant, (Figure 8.4) shows that if the winter component were greater the winds might align better with the dunes.

It is the emphasis on the importance of the winter winds in aligning the mean wind with the dunes that encouraged many authors (Bowler, 1976; Hubbard, 1995b) and Hesse, pers. comm. 2001 to suggest that the winter circulation was more prevalent at the time that the dunes formed. Conceptual models of the climate at the time of dune formation to achieve this include a bulk northward shift of the mean circulation conditions or a strengthening of the westerly winds.

At present the mean wind speed (irrespective of direction) is strongest across much of Australia in summer. In the north and the very southern tips of the continent and Tasmania this is not the case. The seasonal progression in wind speed from the NCEP2 match the findings of Brookfield (1970) for southern Northern Territory. This indicates that the seasonal changes in wind speed in this region are consistent in the recent climate since she used much earlier station data and the analysis here was done using 1982-2000 NCEP2.

The orientation of the mean winds interpolated to the dune locations in the MUGCM PD simulation (Figure 8.5) is not the same in all seasons and locations as NCEP2. This is particularly true in the south of the continent during the transition seasons. In the north west the NCEP2 winds appear to have a stronger response to the heat lows in January, with more on-shore winds than in MUGCM, however the MUGCM also shows such on-shore vectors in October. These seasonal differences carry across to the annual averages for the MUGCM (Figure 8.6) where there is a reversal in orientation in the south west, there is a stronger northerly component in the south east and seemingly stronger influence from the extended period of true monsoon flow. There are many regions where PD results agree and also align reasonably closely with the dunes - in the far west, the Simpson desert and the south of the Sandy desert. Since there are differences in the present day winds between NCEP2 and the MUGCM simulation, this study will concentrate on how wind strength and soil moisture modify the strength and orientation of the vectors and in which seasons they best align with the dunes.
8.6.2 Present Day sand shifting potential

Magnitude

The magnitude of the total drift potential is shaded in Figures 8.7 and 8.8, with the same contour intervals as in Kalma et al. (1988), where 0 to 10 is very low sand shifting potential, 10-32 is low, 32-100 is medium and > 100 is high for the seasons. The sand shifting resultant is greatest in January and October using the data from both the NCEP2 (Figure 8.7) and MUGCM PD (Figure 8.8). This is different from the seasonal variation found by Kalma et al. (1988) using only 3pm data. Brookfield (1970) states that including the night-time wind at central Australian stations alters the seasonal pattern of wind strength due to an increase in the night-time wind in summer. The NCEP2 and MUGCM data are 4 times daily.

In the annual plots, the magnitude of the total drift potential is equivalent to Figure 8.2, but the contour interval is that specified by Kalma et al. (1988), with 0 to 23 very low, 23-86 low, 86-312 medium and greater than 312 high. The NCEP2 annual plot, Figure 8.9, has most of the dunefields in the high sand shifting potential category, as does Figure 8.2 although the category for high potential used by Fryberger (1979) is greater than 400. The MUGCM PD annual sand shifting potential, Figure 8.10, shows most of the dunefields with a mid range potential for sand shifting. With present day winds and no other limitations it would be expected that sand would be shifted and dunes would be active.

Vector orientation

July shows the greatest change from the raw winds in the central region for both NCEP2 and MUGCM. The direction of the mean raw winds in the Simpson desert in July is south-easterly, aligned fairly closely to the dunes. Once the sand shifting potential is calculated the NCEP2 vector is now south-westerly while the MUGCM PD vectors are north-easterly. This indicates that there are differences in the winter wind spectrum of NCEP2 and MUGCM.

January also has some vectors that change orientation after the sand shifting equations are applied to raw winds. These are in the region of the true monsoon in the Northern Territory, with some of the summer vectors that reflect the expected on-shore flow rotating to align better with the dunes. This is particularly clear in the NCEP2 results, (Figure 8.3 and 8.7). These results
Figure 8.3: Dune orientation from Wasson (1986) (pale arrows), and the seasonal NCEP/DOE reanalyses II (NCEP2) mean wind vector (dark arrows) and mean wind speed, contour interval 1.0 m s$^{-1}$. (a) January, (b) April, (c) July and (d) October.
Figure 8.4: Dune Orientation (pale arrows) and annual NCEP/DOE reanalyses II (NCEP2) mean wind vector (dark arrows) and mean wind speed, contour interval 1.0 m s\(^{-1}\)
Figure 8.5: Dune orientation (pale arrows) and seasonal MUGCM PD mean wind vector (dark arrows) and mean wind speed, contour interval 1.0 m s$^{-1}$. (a) January, (b) April, (c) July and (d) October.
Figure 8.6: Dune Orientation (pale arrows) and annual MUGCM PD mean wind vector (dark arrows) and mean wind speed, contour interval 1.0 m s$^{-1}$
8.6 Comparison of Present Day wind and dune orientation

Figure 8.7: Dune orientation (pale arrows) and seasonal NCEP/DOE reanalyses II (NCEP2) sand shifting resultant (dark arrows) and mean total drift potential, contour interval 10, 32, 100 m$^3$s$^{-3}$. (a) January, (b) April, (c) July and (d) October.
Figure 8.8: Dune orientation (pale arrows) and seasonal MUGCM PD sand shifting resultant (dark arrows) and mean total drift potential, contour interval 10, 32, 100 m$^3$s$^{-3}$. (a) January, (b) April, (c) July and (d) October
8.6 Comparison of Present Day wind and dune orientation

Figure 8.9: Dune Orientation (pale arrows) and annual NCEP/DOE reanalyses II (NCEP2) sand shifting resultant (dark arrows) and mean total drift potential, contour interval 23, 86, 312 m$^3$s$^{-3}$
Figure 8.10: Dune Orientation (pale arrows) and annual MUGCM PD sand shifting resultant (dark arrows) and mean total drift potential, contour interval 23, 86, 312 m$^3$s$^{-3}$. 
8.6 Comparison of Present Day wind and dune orientation

indicate that the orientation of the vector produced by summing the cube of the stronger, sand shifting, winds can align less well with the dunes in some seasons than the vector produced by summing all winds.

As the dune direction is the result of the full annual cycle of winds, the annual plots of the sand shifting potential are presented in Figure 8.9 for NCEP2 and Figure 8.10 for MUGCM PD. Although some seasons show large differences in orientation, the annual resultant shows no greater rotation from the mean wind than 60°. The annual rotation for NCEP2 is generally clockwise, as shown in Figure 8.11. The mean wind matches the present day sand drifts and dune extensions better, while the sand-shifting component is rotated to include a more westerly component and align with the relict dunes more closely. The generally consistent clockwise rotation from the mean wind to the direction of the sand shifting potential indicates that, given the PD wind spectrum, reconstructions of the mean annual winds from dune orientations must account for an anti-clockwise shift across much of Australia.

It is not immediately clear why the stronger winds might produce a clockwise rotation in the direction of the mean wind vector. In the south of the continent, most of the mean wind is southerly, thus a clockwise rotation indicates that more strong winds have a westerly component. This is probably due to the strong prefrontal winds from the north-west. In the north-central part of the country the clockwise shift is all in January, which might be expected to be the month with occasional strong winds contributing to the resultant, with increased storminess during the monsoon season although the mean wind is light. In the east there is anti-clockwise rotation, for no clear reason. The anticlockwise change on the northwest coast show some increased easterly influence in January, but the signal is not clear. This rotation of the resultant vector when the strong winds are given greater weighting highlights the conditions under which strong winds might be expected, such as prior to fronts, and during the monsoon.

8.6.3 Present Day sand shifting potential including the influence of soil moisture

The fact that many of Australia’s inland dunes are not active today although they have a medium to high sand shifting potential (Figure 8.2) indicates that there are likely other limiting factors on dune movement. Soil moisture binds the surface, and increases the threshold velocity that the wind must reach to
shift sand. An estimate of how the soil moisture binds the grains of the surface has been estimated in Equation 8.10 and this is applied to both the NCEP2 and MUGCM PD data.

Including the limiting effect of the soil moisture as well as the winds in the NCEP2 data results in vectors of negligible magnitude in each season (not shown). As mentioned earlier the soil moisture available from NCEP2 is persistent and probably is allowed to influence the surface from a depth deeper than the surface layer from which the sand will be deflated. Thus the influence of the soil moisture is likely to be too large. The MUGCM includes soil moisture for only the surface layer which thus responds rapidly to changes in surface moisture and radiation.

In the MUGCM PD, the inclusion of the influence of soil moisture on the sand shifting potential, Figure 8.12 results in a strong reduction in the magnitude of the potential, with almost all regions and seasons in the low and very
8.7 LGM winds and sand shifting potential

8.7.1 LGM winds

The mean LGM wind speed shown in Figure 8.14, when compared to the PD MUGCM simulation, is generally stronger in the north in all seasons, particularly winter. Across central Australia the wind speeds are similar between the PD and LGM simulations, while along the southern coasts the simulated LGM winds are weaker.

The vector orientations are also different between the LGM and PD simulations in some seasons. In the north in October the PD simulation has on-shore mean winds, while the LGM simulation does not show any locations with an on-shore vector. This change indicates a shortening of the season with summer on-shore monsoon winds. In the southwest there is a complete reversal of the vectors in October compared to the PD, and more of an easterly component than westerly in July, showing strong evidence of the shift in the westerlies between the PD and LGM simulations. In the southeast the orientation of the vectors in January and July are similar between the PD and LGM simulations, but in the transition seasons there is a more westerly component. This leads to the annual average (Figure 8.15) aligning to the relict dunes more closely in the LGM simulation than in the PD in the southeast. The disparity in response to...
Figure 8.12: Dune orientation (pale arrows) and seasonal MUGCM PD sand shifting resultant including the influence of soil moisture (dark arrows) and corresponding mean total drift potential, contour interval 10, 32, 100 m$^3$s$^{-3}$. (a) January, (b) April, (c) July and (d) October.
Figure 8.13: Dune Orientation (pale arrows) and annual MUGCM PD sand shifting resultant including the influence of soil moisture (dark arrows) and corresponding mean total drift potential, contour interval 23, 86, 312 m$^3$s$^{-3}$
the shift in the westerlies between the east and the west shows that there was
not just a simple latitudinal shift in the westerlies between the simulations, but
that there is longitudinal variability to the change across southern Australia
(see Figure 5.5).

8.7.2 LGM sand shifting potential

The shift in rotation between the orientation of the mean wind resultant at
the dune sites and the sand shifting potential provides an appreciation for the
wind spectrum in the LGM simulation. Figure 8.16 shows the sand shifting
potential for the mid-month in each season. In January there is little change
between the two across much of the continent, except in the north. Vectors in
the north show a southerly component extending further north, and it looks like
the northerly and easterly component from the monsoon only influence the very
northern-most vectors. This suggests that the winds from the ‘true’ monsoon
are not strong in the LGM simulation. There is little change in April, except for
a few vectors just north of the Great Australian Bight turning southward. This
southward turning affects vectors further inland in July, indicating that strong
northerlies are important in southern Australia in the LGM simulation. In Oc-
tober there is little change except in the southeast, where the influence from the
northerlies is again noticeable. In the annual mean (Figure 8.17) the contours
of the LGM total sand drift potential closely follow those of the LGM mean
annual wind. There is little change in orientation across the continent, except
in the southeast, where the influence from enhanced northerlies is evident.

8.7.3 LGM sand shifting potential including soil mois-
ture

It has been shown that the conditions at the LGM were generally drier, and thus
the inclusion of soil moisture might be expected to have less effect in the LGM
simulation than for the PD. Figure 8.18 shows the anomaly of the mean total
drift potential, including the influence of soil moisture, between the LGM and
the PD MUGCM simulations. The results across the majority of the country
show that, in the drier environment at the LGM, the sand shifting potential is
higher, particularly along the southern coast. The positive anomaly along the
southern coast is strong in all seasons.
Figure 8.14: Dune orientation (pale arrows) and seasonal MUGCM LGM mean wind vector (dark arrows) and mean wind speed, contour interval 1.0 m s$^{-1}$. (a) January, (b) April, (c) July and (d) October.
Figure 8.15: Dune Orientation (pale arrows) and annual MUGCM LGM mean wind vector (dark arrows) and mean wind speed, contour interval 1.0 m s$^{-1}$
Figure 8.16: Dune orientation (pale arrows) and seasonal MUGCM LGM sand shifting resultant (dark arrows) and mean total drift potential, contour interval 10, 32, 100 m³s⁻³. (a) January, (b) April, (c) July and (d) October
Figure 8.17: Dune Orientation (pale arrows) and annual MUGCM LGM sand shifting resultant (dark arrows) and mean total drift potential, contour interval $23, 86, 312 \text{ m}^3\text{s}^{-3}$
The introduction of the limitation of soil moisture on soil movement in sand shifting potential equations using the MUGCM LGM results strongly reduces the potential for sand to be shifted (Figure 8.19), as in the PD MUGCM simulations. Hence it generally does not produce a systematic shift in the vector orientations from the sand shifting potential without the influence of soil moisture (Figure 8.16). However, there are some vectors that shift their alignment to be very close to the relict dunes: two just west of Spencer Gulf in South Australia in October, and two of the vectors on the eastward edge of the dunes in New South Wales in July. In the annual average (Figure 8.20) it is these dune sites that show the strongest change from the sand shifting potential calculated without the influence of soil moisture (Figure 8.17). The vectors for the LGM sand shifting potential, including the influence of soil moisture, align well with dunes in the Simpson Desert, as do the mean winds and the PD reanalyses and simulations. Elsewhere, particularly in the south, the vectors do not align well with the relict dunes.

Figure 8.18: LGM minus PD total drift potential, including the influence of soil moisture, from the MUGCM simulations. Contour interval: $20 \text{ m}^3\text{s}^{-3}$, negative contours are dashed and the zero contour is bold. Arrows are the dune orientations from Wasson (1986).
Figure 8.19: Dune orientation (pale arrows) and seasonal MUGCM LGM sand shifting resultant including the influence of soil moisture (dark arrows) and corresponding mean total drift potential, contour interval 10, 32, 100 m$^3$s$^{-3}$. (a) January, (b) April, (c) July and (d) October.
**Figure 8.20:** Dune Orientation (pale arrows) and annual MUGCM LGM sand shifting resultant including the influence of soil moisture (dark arrows) and corresponding mean total drift potential, contour interval 23, 86, 312 \(\text{m}^3\text{s}^{-3}\).
8.8 Synopsis and discussion

New data and model simulations have presented the opportunity to re-assess the drivers behind the PD and historic sand movement across Australia, and potentially build an improved understanding of the circulation at the LGM. The limitations on sand movement and the relationship between the climatic environment and resultant dune orientations have been addressed in a number of new ways.

Global, six hourly, gridded wind data has been used to determine the potential for dune building globally. The results across Australia indicate that, under the present wind regime, most of Australia’s dunefields are in an environment conducive to dune-building today. This result is likely to be more accurate than the results of Kalma et al. (1988) because he only used the winds at 3pm, which, according to Brookfield (1970), fail to capture the strong winds at night in central Australia. This result suggests that, since there is limited sand movement or dune building today, there must be limiting factors other than the wind regime preventing such activity.

To better understand the circulation that led to the formation of dunes across Australia, the orientations of the historic dunes (and present day sand drifts and dunes) across Australia were compared with the mean wind vectors, the resultant vector of the sand shifting potential, and vectors of the sand shifting potential including the influence of soil moisture. For the present day, the vectors of the annual mean wind from NCEP2 for 1982-2000 show close alignment with the dune orientation in the Simpson Desert, further north and on the west coast. In the south there is good alignment with the present day sand drift and dune building, but not so close alignment with the relict dunes. Calculating the sand shifting resultant produces a rotation to the right of the mean wind at all but a few dune locations across Australia. This rotation varies in magnitude across the continent, with less in the north central region (the Simpson and Sandy Deserts) and more in the southern half of the continent. The degree of rotation is a reflection of the degree of directionality of the wind. If all winds are from one direction, there will be no change in orientation between the mean wind vector and the sand shifting resultant. The present day sand movement might be expected to align better with the sand shifting resultant, and their vectors are similar, but the mean wind is closer. In the south the vectors of sand-shifting potential are closer to the the relict dune orientation
than the mean wind. The binding influence of soil moisture removes any sand moving potential.

The orientation of the annual mean wind vectors at dune locations in the MUGCM simulation of the present day show a stronger influence from the summer winds in the north, and the winter winds in the south than NCEP2. The magnitude is lower right through central Australia in the MUGCM. The main reasons for the differences between the MUGCM and NCEP2 averages are likely due to differences in the models, and the fact that NCEP2 has observations assimilated. The results from each are for different periods, which would also contribute to differences seen: the MUGCM simulation for the present day is driven by sea surface temperatures averaged from 1982 to 1987, while the NCEP2 results are averaged over the years 1982-2000.

The MUGCM PD sand shifting vectors do not change orientation a great deal from the mean wind except in the north, where they become aligned with the sand-shifting potential in NCEP2. The inclusion of the binding effect of soil moisture will have a different signature in the MUGCM to that in the NCEP2 data because the NCEP2 soil moisture anomalies are more persistent. There was some potential for sand shifting with the influence of soil moisture included, though it is greatly reduced. Most of the vectors have a similar orientation to the sand-shifting potential; but in the southwest the change is marked, with an almost complete reversal as the vectors shift from an orientation close to the winter vector to one closer to the summer vector. This is due to the rainfall regime in the southwest, with the majority of the annual rainfall falling in winter.

The LGM results do not lead to a closer alignment with the relict dunes than the present day simulation and data except in the north west. In the south, the large-scale southward shift in the westerlies in the Australian region at the LGM causes the mean seasonal LGM winds to generally align less well in winter and spring than the PD winds, however the mean winds in the Mallee in south eastern Australia align well. Limiting the vectors to the stronger winds in calculating the sand shifting potential leads to strong northerly winds in the south east in autumn, winter and spring, causing the mean annual vector to be less well aligned with the relict dunes. Interestingly, this strong change did not occur with the PD data. Strong northerly winds in this region are generally linked to pre-frontal activity, thus this probably reflects the increased number of, albeit weaker, cyclones across southern Australia in the LGM simulation.
The inclusion of soil moisture has a significant effect on the vectors in the Mallee region in October and on the Lake Eyre peninsula. The shift in the precipitation regime is most likely due to the anomalously warm SSTs off the east coast shifting the path of moisture over eastern and southern Australia.

In the present day, there is strong on-shore afternoon flow over the southern coast in all seasons except winter. This flow is likely stimulated by the pressure differences between the warm land and cooler ocean as the land heats up during the day. As the average temperature of the land mass cooled at the LGM, this will have had an influence on the orientation of the winds in the warmer months, particularly in the transition seasons, bringing the sand shifting vectors more into line with the relict dunes. As the simulation of the LGM failed to produce such marked cooling as suggested by the proxies, this might lead to continued on-shore flow in the MUGCM in those seasons that would not have occurred with a cooler continent.

Potential stresses on vegetation growth at the LGM such as decreased atmospheric carbon dioxide, decreased temperature and lower precipitation will all contribute to a reduction or change in vegetation at the LGM. There is no vegetation described in the MUGCM simulations, but, following Ash and Watson (1983), it was shown that the soil moisture can represent the influence of vegetation on the mobility of dunes. As the annual LGM soil moisture is less than the PD, it suggests that the LGM mobility would be increased in these simulations due to decreased potential for vegetation growth.

The limiting effect of soil moisture as parameterised here is a strong factor in sand movement, and the seasonality and amount of precipitation will have a large influence on which winds are included in the sand shifting resultant, and hence the final orientation of the dunes. A good example of this is in the southwest where there is a winter rainfall regime. In the MUGCM PD simulation the aeolian landforms suggest a strong north westerly component to the wind, which is the more dominant wind in winter. However this wind component is not included in the sand shifting winds once the limiting nature of soil moisture is included. If the conditions were much drier, the winter winds would be included in the sand shifting resultant, leading to vectors more closely aligned to the aeolian landforms. The surface-binding influence of soil moisture is most likely a strong contributor to the limited sand movement today. This result suggests that if regions of Australia become drier in the future, but the wind regime remains similar to today, there will be increased erosion, sand
movement, and potentially, dune building.
8. Dunes as a proxy for wind
Chapter 9

Conclusions

This thesis has aimed to further our understanding of both the observed and modelled weather and climate of Australia at the Last Glacial Maximum (LGM), some 21,000 years ago. This study is the first using all the models from the PMIP, allowing for a strong test of how different models respond to the same LGM boundary conditions. The high temporal resolution output of the MUGCM has also provided an opportunity to examine the circulation shifts and hydrological cycle in detail.

Reconstructions of the LGM climate from proxy evidence in the literature suggest cooler conditions prevailed in central and south east Australia, along with drier conditions, particularly in the continent’s interior. Further proxy evidence suggested a greater level of wind blown sediment at the LGM.

The PD simulations from each of the models were compared against present day mean temperature, precipitation totals and their seasonality. One of the models failed to represent the appropriate seasonal cycle. The differences between the PD and LGM simulations were then considered and two of the models produced an unexpected response to the LGM forcing. The results from these three models were treated with caution. The LGM results from the other models were cooler and drier, in line with the proxy evidence. The differences in the surface temperature and precipitation response between the models was due more to the surface parameterisation than the model resolution, though the height of the lowest model level was important for simulating the surface winds correctly. The MUGCM results were amongst those considered to be the most consistent with both the PD data and LGM proxy reconstructions.

The LGM simulation with the models did not produce as strong a cooling across Australia as suggested by the proxies. This may be due to errors in how
the GCMs respond to the LGM boundary conditions, or it may be due to errors in the CLIMAP boundary conditions. The models used are only atmospheric models, and thus any interaction with the ocean will not be included in the response. The response of the atmosphere however, is consistent across the models. Using so many models with different resolutions, dynamic cores and parameterisations but the same boundary conditions indicate that the response across Australia is not simply due to errors in how any one model responds to the boundary conditions, and that the response is consistent with the drivers.

Of all the LGM boundary conditions imposed, the SSTs and lowered atmospheric carbon dioxide levels were the strongest contributors to the cooling over Australia in the MUGCM. Both these boundary conditions are based on reconstructions from proxy evidence, which has its own error bounds, and there are a number of suggested changes to the CLIMAP reconstructions in the literature. Modifications to these boundary conditions following those suggestions were implemented to test if these changes might bring the simulated temperature in line with the proxy evidence. Reducing the carbon dioxide to the lower end of the range reconstructed for the LGM produced a greater cooling over Australia as might be expected, but further reduction of the carbon dioxide levels did not produce great changes, highlighting the potential non-linearity in the response to carbon dioxide levels. Updating the local LGM SSTs in the Australian region to those suggested in the literature led to a shift in the cloud and precipitation across the continent and little change in the temperature. The greatest temperature reductions were produced by a global reduction of the CLIMAP SSTs by 1°C or a ‘flattening’ of the temperature anomalies across the tropical Pacific. These results highlight the importance of accurate ocean temperature reconstructions from proxies when trying to understand the changes over land. The temperatures simulated under each of these tests were not as cool as the temperatures reconstructed from the proxies.

These sensitivity tests highlight that, even with quite extreme changes to the most important boundary conditions, the temperatures simulated across Australia were still not as cool as the reconstructed LGM proxy evidence. Thus there is still some aspect of the models that is not able to produce the cooling seen from proxies. The next phase of PMIP, with coupled models, may help unravel this problem.

Australian rainfall is strongly influenced by the surrounding oceans, as shown by the low values of the moisture recycling ratio (the ratio of precipita-
tion that is derived from moisture evaporating locally to the total precipitation) calculated in this thesis. Regionally, across the seasons, and between the two methods presented, there was some variation in the sign of the changes in the moisture recycling ratio between the LGM and the present day. In general the LGM hydrological cycle was weakened, with lower mean precipitable water and not only decreased local actual evaporation from the drier surface, but also less moisture advected across the continent. Although the changes in the recycling ratio were mixed, the decreases in advected moisture in all seasons and all regions except the south west indicate that the lowered sea-level and less vigorous hydrological cycle led to greater isolation of the continental interior from external influences at the LGM. This would contribute to drier conditions in inland Australia, in accordance with the proxy evidence.

An apparent enigma in the proxy evidence at the LGM is the high lake levels in Australia’s south east, while most inland lakes were dry. The reconstruction from surrounding vegetation is of drier LGM conditions. Previously it was thought that the high lake levels were due to a decrease in the potential evaporation (due to the cooler temperatures) at the LGM or an increase in the run-off and snowmelt. In the model simulations in this thesis, the potential evaporation was always far higher than the precipitation across Australia, thus lakes would always be limited by the amount of inflow rather than evaporation. In the south east the model simulates a decrease in precipitation at the LGM, which would result in lake levels lower than at the PD. If these modelled results are an accurate measure of the balance between precipitation and evaporation it suggests that the high LGM lake levels were due to changes in the run-off regime.

There is debate in the literature about the interpretation of the proxy evidence for the LGM circulation, and whether it indicates a meridional shift in the track of the westerlies. If such a shift occurred, it is unclear from the proxies whether this was to the north or south of the current path. Such shifts have consequence for the climate of southern Australia. All the models examined in this thesis simulate a southward shift in the westerlies in the Australian region. In the MUGCM this is strongly driven by the meridional temperature gradient in the prescribed SSTs north of the LGM Antarctic sea-ice edge. This is a robust response, as a southward shift was seen even when the SSTs presented to the model were modified to agree with newer SST estimates from marine proxies.
Relict continental dunes are a major proxy for past winds across Australia, and the controls on their development were re-visited. A dune’s formation and orientation is linked to the frequency and timing of the winds strong enough to shift sand and conditions dry enough for the sand to be shifted. This means that dune formation can be linked to specific weather events, that only happen at certain times of year. While Australia’s present day wind regime is conducive to dune building, the relatively wet conditions shown in the present day data and model simulation mean that the binding effect of soil moisture is strong enough to limit dune movement. However, it has been shown from the simulations here that in the drier climate at the LGM there was a capacity for sand movement. The inclusion of soil moisture as a limiting factor on sand movement can alter the seasons in which the wind can shift sand. For example in the south west, that has a winter rainfall regime, the summer winds dominate once soil moisture has been included in the calculation of the sand shifting potential.

The orientation of Australia’s inland dunes is one of the indicators of past circulation regimes. The orientation of the vectors of the mean wind, the sand shifting potential (that only includes the strong, sand shifting winds) and the sand shifting potential with the limitation of wet sand, was compared to the dune orientations. There was a consistent clockwise shift in the PD vector orientations from the mean wind to the sand shifting potential (except on the north west and south east coasts). As the known limitations of wind speed and surface binding features such as soil moisture are included in the calculation of the dune orientation, seasonal variability such as a winter rainfall regime become paramount. These factors must be accounted for when using dune orientations as a proxy. Across much of the Simpson Desert all wind measures match the dunes, as the wind there has little variation through the seasons or between the data and different simulations. In the north, the seasonal averages show fewer winds with an on-shore component in the LGM simulation, which leads to mean winds that align with the relict dunes more closely than the present day simulation. Once the strong, sand shifting winds only are considered, the present day results also match the dunes in the north. Across the south of the continent the on-shore flow in all seasons but winter in the present day leads to vectors with a strong on-shore component, that do not match the relict dunes. The sand shifting vectors, however, are rotated to the right of the mean wind, and align closer to the dunes. The southward shift in the LGM winds does not lead to a better match with the relict dunes. The large-scale southward shift...
is a robust feature of the simulated LGM climate, as mentioned above, but the fact that the model does not capture the extreme continental cooling and there is an anomalous hot spot in the east coast SSTs might alter the exact location and timing of weather events required to accurately represent the dune vectors.

The LGM simulation shows large-scale circulation shifts across southern Australia. The drivers of the modelled circulation changes include a weakened Walker circulation, a Hadley circulation that is both weaker and extended further south, and a drier atmosphere. The understanding of these drivers of the extreme LGM climate has helped better understand what might be driving such southward shifts in the present day.

The analysis performed in this thesis shows that our capacity to simulate climates quite different from the present is still developing, but that model results can help explain apparent inconsistencies in the reconstruction of past climates from proxies. Although the LGM climate across Australia may be more subtly different from the present day than elsewhere around the globe, there is a clear preference in the models to simulate a southward shift in the westerlies in the Australian region, and the increased continentality of Australia’s inland climate from both lowered sea-levels and less moisture advection onto the continent is also clear. The simulated changes illustrated here in the LGM weather and climate for Australia have helped explain some of the drivers of Australia’s circulation and hydrological cycle. These facts will not only help us better interpret the LGM climate but also help us understand the climate shifts that we are currently seeing that will become more dominant into the future.
References


REFERENCES


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REFERENCES


Pickett, E. J. (1997). *The Late Pleistocene and Holocene vegetation history of three lacustrine sequences from the Swan Coastal Plain, southwestern Australia*, PhD thesis, The University of Western Australia, Western Australia, Australia.


Simmonds, I., Trigg, G. and Law, R. (1988). The climatology of the melbourne university general circulation model, Pub. no. 31, Department of Meteorology, University of Melbourne. [NTIS PB 88 227491.]


Smith, B. L. (2002). Optically stimulated luminescence dating of Quaternary landforms in southeastern Australia, PhD thesis, LaTrobe University, Melbourne, Australia.


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